Factors in the Ocular Accommodation Response to Single and Multiple Stimuli

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B App Sc (Optom) (Hons)

Submitted in partial fulfilment of
the degree of Doctor of Philosophy

School of Optometry
Queensland University of Technology

1995

QUEENSLAND UNIVERSITY OF TECHNOLOGY
DOCTOR OF PHILOSOPHY THESIS EXAMINATION

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Abstract

I studied a number of factors contributing to the accommodation response for single and multiple stimuli. I first investigated the effects of subject instructions, methods of target presentation, and pupil size on the characteristics of accommodation responses to single targets. I then modelled the accommodation response to peripheral stimuli, and investigated whether the accommodation response to an extended target can be predicted from the responses to its constituent parts. Finally, I investigated the effects of voluntary accommodation, target contrast, upper blur threshold, and adapting level effects on the accommodation responses to conflicting targets, and used control system models to predict these responses.

Previous research has not systematically investigated the effects of *subject instructions* on accommodation. I found that instructions can influence subjects to make voluntary changes in their accommodation or conscious changes in their normal attention to a target.

Although Badal optical systems are widely used in accommodation research, it has not been shown that this method of *target presentation* yields accommodation responses equivalent to those for targets presented in real space. I found that most people can accommodate adequately for steady targets presented in Badal optical systems even though these systems remove many of the proximal stimuli to accommodation normally found in real scenes. However, some people do have difficulty when trying to focus for targets presented in Badal systems.

Previous studies of the effects of *pupil size* on the high frequency fluctuations of accommodation are conflicting. I found that pupil size (1–6 mm diameter) does not influence the high frequency (0.7–2.53 Hz) fluctuations of accommodation. Changes in a high frequency (2 Hz) peak of the power spectrum may be caused by accommodation instability (due to an unknown cause) independent of pupil size. Small pupils lead to an increase

in the low frequency (0–0.63 Hz) fluctuations of accommodation, independent of mean accommodation level and retinal illuminance. These changes in low frequency fluctuations may be due to voluntary, proximal and cognitive influences which have a greater influence when the depth of focus is larger with small pupils.

In my study of *peripheral stimuli* to accommodation I used dynamic target motion to investigate whether 'reflex' accommodation can occur to the blur of a peripheral target. Previous studies used targets which would have encouraged voluntary accommodation. One subject in my study showed evidence of reflex accommodation to peripheral targets while the other may have relied on voluntary accommodation for slowly moving peripheral targets. I also found that accommodation gain and phase lag for dynamic targets (0.02, 0.2, 0.5 Hz) do not improve as a target's size is increased from 0.5° to 3.0° radius, contradicting the view that there is pooling of both central and near peripheral blur signals to the higher accommodation control centres. I developed a dynamic control model of the response to peripheral stimuli but it incorrectly predicted that responses become more accurate with larger targets. The model may have failed because it assumes that people attend equally to both the central and peripheral detail of a target when they actually may selectively attend to the central detail.

I hypothesised that a number of factors may help to explain the wide variability in accommodation responses to *conflicting targets* previously reported in other studies. None of these factors have previously been investigated. I controlled for subject instructions by requiring the subjects to attend to only one target. Many people do not overcome the Mandelbaum effect by using memorised voluntary accommodation to lock on to the memorised focus level of the desired target. People probably use other forms of voluntary accommodation to overcome the Mandelbaum effect. Proximal cues may be used to overcome the Mandelbaum effect, because an interposed mesh did not induce a change in accommodation even when the distant target viewed in real space had low or zero contrast. Conflicting targets can also induce changes in the perceived sizes and distances of

targets. The upper blur threshold of accommodation is unlikely to play a significant role in the responses to conflicting targets. The adapting level of accommodation just prior to viewing a set of conflicting targets sometimes affects the response, but the effect is not consistent or significant.

The possibility of predicting accommodation responses to conflicting targets may not be as bleak as previously concluded by others. I developed control models that perform well in predicting the steady accommodation responses of many subjects to conflicting targets. Some subjects focus for the target that gives a response closest to their tonic accommodation level, while others accommodate for an attended target, apparently ignoring a conflicting target. One control model performs poorly, probably because it assumes that people attend equally to both conflicting targets. Future models of the accommodation response to conflicting targets will need to consider the separate effects of both reflex and voluntary accommodation.

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Statement of Original Authorship

The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Date: 13/1/95

Acknowledgments

I thank my principal supervisor David Atchison for his help and advice at every stage of my research. David also designed the Badal optical system attached to the Ophthalmetron optometer. He oversaw modifications to the Ophthalmetron optometer, construction of the Badal optical system, and development of electronics involved in both controlling the target system and acquiring data.

Herbert Niesler and Djino Pirsic designed electronics that allowed me to both control the Badal targets and acquire Ophthalmetron output with an interfaced computer. Herbert wrote a computer program to perform these various operations. Dean Smith and other staff of Lionel Otto Instruments (Brisbane, Q.) manufactured most of the components of the Badal optical system. I thank Eddie Matejowsky for his technical assistance with the Ophthalmetron system at various times. Brett Davis gave me technical assistance with the two Canon Autoref R-1 optometers I used in my research. I also thank Brett for the use of his power spectrum analysis program, which I used to analyse fluctuations of accommodation.

I was assisted in my research by an Australian Postgraduate Research Award from the Commonwealth Department of Employment, Education and Training. I also thank the Q.U.T. Optometry School for financial assistance it provided.

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Chapter 1

Human Ocular Accommodation

1.1. Introduction

Accommodation refers to the ability of an eye to clearly see objects at different distances in the visual world. The need for accommodation arises because objects at different distances are not all imaged at a single distance within the eye close to the retina. If an object is out of focus by an amount greater than the eye's depth of focus then the object will appear blurred. In the human eye accommodation is achieved by alterations in the shape of the crystalline lens,[1] but there are many other mechanisms, both active and passive, used by other animal species.[2,3]

1.1.1. Definition of Accommodation

According to Duke-Elder and Abrams[4] the term *accommodation* was introduced by Barrow[5] in 1841. A good definition of accommodation has been provided by Cline *et al*:

> Accommodation. Specifically, the dioptric adjustment of the eye (to attain maximal sharpness of retinal imagery for an object of regard) referring to the ability, to the mechanism, or to the process.[6]

1.1.2. Components of Accommodation

Heath[7] proposed an operational classification of accommodation into four components. (1) *Reflex accommodation* refers to the automatic change in focus that occurs to a blurred target. The blur and associated cues stimulate an accommodation response. (2) *Proximal accommodation* is the focusing response stimulated by perceived distance. Heath considered *voluntary accommodation* to be simply an exaggerated form of proximal accommodation. (3) *Convergence accommodation* is the accommodation that results from a change in convergence in the absence of any stimulus to accommodation. (4) *Tonic accommodation* is the accommodation state adopted in the absence of any stimuli.

1.2. Characteristics of the Response of Accommodation

1.2.1. Accuracy of the Accommodation Response

The accuracy of accommodation can be assessed by presenting a target to a subject at different distances from the eye and then recording the accommodation response for each target distance after the response has reached a steady value. A plot of the accommodation response as a function of the accommodation stimulus yields the accommodation stimulus–response function. Although there are many factors that influence the shape of this function, it generally has a sigmoid shape[8-14] which Ciuffreda[15] divided into six regions.

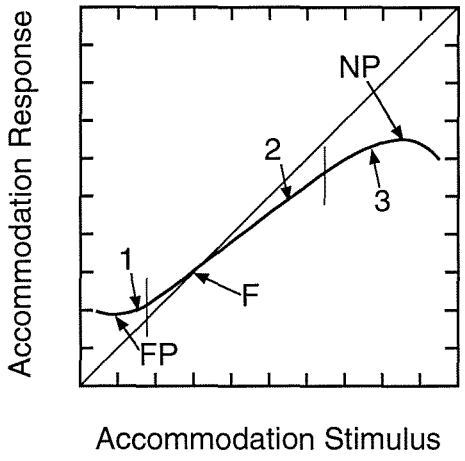


Figure 1.1. Schematic accommodation stimulus–response function. The accommodation response is plotted as a function of the accommodation stimulus. Key: lower non-linear region (1); linear region (2); upper non-linear region (3); accommodation far point (FP); accommodation fulcrum position (F); accommodation near point (NP).

I have divided the stimulus–response curve into three regions with three reference points, shown schematically in Figure 1.1.

The three regions are: (1) Lower non-linear region; (2) Linear region; (3) Upper non-linear region. The three reference points are: (1) Accommodation far point;[11] (2) Accommodation fulcrum position; (3) Accommodation near point.[11]

In the *lower non-linear region* there is a non-linear relationship between accommodation response and accommodation stimulus. At a certain point accommodation reaches its minimum value, the *accommodation far point*. In monocular viewing the far point has typical value of between 0 D and 1.00 D.[8,16-18] Note that the accommodation far point is (usually) different from the true far point obtained in cycloplegia.[19]

The reasons for the far point and the non-linearity may be a difficulty of the ciliary body to relax accommodation when the crystalline lens is close to its maximally flattened state. Another possibility is that the tonic accommodation level may have a greater influence on the response in this region[20] especially if the target is within the depth of focus of the tonic

resting level of accommodation. The spherical aberration of the eye has been speculated to provide some of this depth of focus.[8] Some subjects have difficulty relaxing accommodation in Badal systems and exhibit a high accommodation far point (see Chapter 3).[18] The difference between the accommodation far point and true far point also depends on the refractive error of the eye.[19]

As the target is moved even further in the hyperopic direction (beyond infinity) the response increases again and asymptotes at a level close to the tonic resting level.[9,18] This is probably because as the target becomes increasingly blurred, there is a reduced stimulus to accommodation due to the loss of first high and then mid spatial frequency information.

In the *linear region* there is a linear relationship between the accommodation stimulus and response. A best fit line to the data in this region usually has a high slope close to +1 (approximately +0.8 – +1.0),[14,21] but sometimes greater than +1,[22] and sometimes much less than +1 (≈0.5).[23] When the slope is very close to +1, accommodation can either be very accurate for the target or can lag behind or in front of the target by a small amount. Accommodation usually *lags* behind the target when the target is close to the eye, but the response *leads* the target when the target is more distant from the eye. These lead-lag characteristics[9,11,14,17,21,24,25] have been interpreted as evidence for *proportional control* in the accommodation system,[26] although Kasai *et al.*[27] and Krishnan and Stark[28] argued against proportional control. Krishnan and Stark argued that the increased lag of accommodation at higher stimulus levels found in many studies could be due to a reduction in the size of the natural pupil and consequently an increase in the depth of focus.[28] However, in other studies that have controlled pupil size artificially there still is evidence for proportional control.[11,17,24]

In many subjects there is a particular accommodation response level where the response and stimulus match exactly: the *accommodation fulcrum position*. It is called a fulcrum because in some subjects,[17,29] but not in all subjects,[24] this point appears to be constant regardless of the slope of the

stimulus–response function (within limits) and is close to the tonic resting level of accommodation. In group studies there is a significant correlation between the fulcrum position and the dark focus, but the two values can differ by large amounts for individual subjects.[17,23,24] A difficulty in these comparisons is that as the slope of the function approaches +1, the measured fulcrum position becomes ever more sensitive to small errors in the intercept of the stimulus–response function. (The change in fulcrum position is proportional to $1/(1-slope)$ multiplied by the change in intercept).

If the target is moved relatively close to the eye the relationship between response and stimulus again becomes non-linear:[8,9,14,18] this is the *upper non-linear region*. The accommodation response can be more variable in this zone as the subject makes an effort to maintain a high focus level.[18] At a certain point the maximum accommodation level is reached: the *accommodation near point*.[11] As the target is moved even closer to the eye the response can decrease, probably due to increasing target blur and loss of high and mid spatial frequency information.

The main factor influencing the accommodation near point is the loss of accommodation amplitude due to presbyopia.[10] However it should be noted that the accommodation near point can vary depending on characteristics of the accommodation stimulus such as its luminance.[11,29]

1.2.1.1. FACTORS IN THE ACCURACY OF THE ACCOMMODATION RESPONSE

There are numerous influences on the accuracy of accommodation, some of which have been mentioned in the preceding discussion, and these will be dealt with in depth in later sections.

An organising theme for many of these factors is that the accommodation stimulus–response slope decreases when the adequacy of the stimulus to accommodation is reduced — eventually the slope reaches zero and the resting level of accommodation is maintained.[30] Examples are the reductions in stimulus–response slope with decreasing luminance[11,29] and with smaller pupils,[17] among others.

1.2.2. Fluctuations of Accommodation

During steady viewing of a target the accommodation response is observed to fluctuate by a small amount around the mean accommodation level. These fluctuations are also present when viewing dynamic targets although they are best observed with steady targets. These *fluctuations* of accommodation are also known as *microfluctuations* of accommodation. Early descriptions of accommodation fluctuations were qualitative.[31,32] Later, Arnulf and colleagues used double-pass ophthalmoscopic methods to study the fluctuations of accommodation,[33-39] while others used stigmatoscopic methods,[40] a subjective vernier optometer,[41] or Purkinje image cinematography.[42] However all these methods lacked the time resolution needed to adequately study the temporal characteristics of the accommodation fluctuations. Campbell, Robson and Westheimer were the first to study the temporal characteristics of accommodation fluctuations[43-46] using their continuously recording infra-red optometer.[47] Other studies have used Campbell's optometer,[48] other purpose built optometers,[18,25,49,50] or modifications of clinical infra-red optometers.[51,52]

1.2.2.1. MAGNITUDE AND FREQUENCY CHARACTERISTICS OF FLUCTUATIONS

The r.m.s. value* of the fluctuations of accommodation varies with the mean response level and other factors, but has a typical value of up to 0.4 D.[25,51,53,54] The fluctuations are dominated by low frequency oscillations in the range 0 Hz to 0.5 Hz, and also include a high frequency component whose peak frequency varies from subject to subject but typically is in the range 0.9 Hz to 2.5 Hz.[18,25,45,51,52,54,55] The strength of oscillations at other frequencies falls off with increasing frequency, and it is thought there is a negligible content of oscillations at frequencies greater than 5–6 Hz,[25,56] although this cut-off value will depend on the degree of noise in a particular optometer's output signal.

Although many studies have found a high frequency peak in the power spectrum of accommodation fluctuations, there is controversy over the

* The r.m.s. value is the standard deviation of the response, and its unit in this case is dioptres.

magnitude of this peak and whether it is a constant feature of the accommodation fluctuations. For example, Kotulak and Schor found that the amplitude of the high frequency peak varied between just 0.02 D and 0.1 D, depending on the subject and stimulus level.[51] These magnitudes are very small. Also, a high frequency peak was not always present in accommodation recordings in some studies.[46,57]

It is possible that the fluctuations in the two eyes are highly correlated, based on visual inspection of Campbell's data.[46] However no-one has yet attempted to gather enough data to statistically test this hypothesis. This correlation of fluctuations between the two eyes could be due to the consensuality of the efferent neural signals to the two eyes,[46] or it could be due to some external influence (e.g. arterial pulse) that influences both eyes almost equally.

The fluctuations of accommodation are very similar when measured through central and peripheral portions of the pupil.[55] There is a loose correlation between the fluctuations of accommodation and fluctuations in eye position.[58]

1.2.2.2. VISIBILITY OF FLUCTUATIONS OF ACCOMMODATION AND THEIR EFFECT ON VISUAL ACUITY

The magnitude of the fluctuations of accommodation are close to typical values for the depth of focus of the eye, and so the fluctuations are sometimes visible.[53,59,60] Millodot found that visual acuity improved slightly (but not significantly) when the fluctuations of accommodation were reduced with cycloplegia.[61]

1.2.2.3. DEPENDENCE OF FLUCTUATIONS ON MEAN ACCOMMODATION RESPONSE LEVEL

Early studies found that the r.m.s. value of accommodation fluctuations increases with the mean accommodation response level, and is minimal at the far point[25,36,49,51] — not at the dark focus or resting level of accommodation.[51] (See Charman and Heron[56] for a graphical comparison of the results of these studies.) A recent study by Miege and Denieul[18] over a

much larger stimulus range found that, for two subjects, the fluctuations are minimal at the far and near points of accommodation and maximal at an intermediate level of accommodation. It has been hypothesised that a reduction in the fluctuations at the near and far points is due to the resistance of the crystalline lens to fluctuations in power when it is maximally rounded at the near point or maximally flattened at the far point.[18,51,56]

One study has found that the magnitude of the high frequency oscillations increase with the mean accommodation response level and this could be due to active neurological enhancement or simply a passive increase in noise along with increasing noise at other frequencies.[51] The findings of two other studies suggest that the magnitude of the high frequency oscillations are maximal at an intermediate accommodation response level.[18,25]

The magnitude of low frequency components of the accommodation fluctuations, like the r.m.s. value, is possibly greatest at intermediate accommodation response levels and decreases towards the far and near points.[18,25]

1.2.2.4. SOURCES OF FLUCTUATIONS OF ACCOMMODATION

Source of High Frequency Fluctuations

The source of the high frequency fluctuations of accommodation has been a contentious issue. The three main views are that the high frequency fluctuations are: an intrinsic part of accommodation control; or a 'nonfunctional indicator of the nonlinear characteristics of the accommodation servo-mechanism';[62] or are due to the ocular pulse.

Numerous authors have suggested that accommodation fluctuations are involved in the accommodation control process (see later). However the high frequency fluctuations do not consistently change with stimulus conditions such as pupil size and luminance and are thus unlikely to represent active neural control.

Stark and colleagues, based on a study of the accommodation response to sinusoidal targets, discounted the high frequency fluctuations of accommodation (at 2 Hz) as nothing more than a borderline instability of the accommodation control mechanism, possessing no functional significance.[48,62] Stark's study has been criticised because his control model uses an unrealistically small value for the system dead time, more realistic values giving a system instability at about 0.45 Hz instead of 2 Hz.[63] However it should be noted that a 2 Hz instability was present in the experimental data from two subjects, and thus is not simply the product of an inadequate model. It has been suggested that a frequency of 2 Hz may be a resonant frequency of the ciliary body–zonular fibre–crystalline lens system, reflecting its mechanical characteristics.[56] Campbell and colleagues doubted that the 2 Hz peak was a resonant frequency of the accommodation system because if it were then there should be a 2 Hz instability following a step change in accommodation, and there was no evidence at that time of such an instability.[45] However, Sun *et al.* have recently demonstrated the presence of such a 2 Hz peak when subjects track a step stimulus.[64]

The most compelling evidence to date demonstrates that the presence of a high frequency fluctuation peak is due to the ocular pulse. Interestingly, Allen in 1955 suggested that the ocular pulse could be associated with the fluctuations of accommodation.[42] It was not till recently that a number of researchers demonstrated that the high frequency peak of the accommodation fluctuations is almost perfectly correlated with the arterial pulse rate, both between and within subjects.[52,54]

A number of suggestions have been made for a mechanism by which the arterial pulse causes fluctuations in accommodation.[52,54] Firstly, changes in axial length due to pulsatile changes in choroidal blood volume are too small to account for the magnitude of the fluctuations.[52] Importantly, high frequency fluctuations are present in phakic eyes of young subjects but not in their fellow aphakic eyes,[52] showing that the crystalline lens must be present for the fluctuations to become manifest. This leaves two other mechanisms: pulsatile changes in the ciliary body blood volume and/or

small axial shifts in the position of the crystalline lens due to the intra-ocular pressure pulse. Collins *et al.*[a] calculated that a 0.25 D fluctuation in accommodation would require a 200 μm oscillation in axial lens position.

A finding that is not explained by the arterial pulse theories is one reported by Campbell, Robson and Westheimer.[45] They noted that a 2 Hz peak which was present in steady viewing disappeared when the subject followed a sinusoidal target at 2.8 Hz. If the high frequency peak were simply a passive response of the lens to the ocular pulse then we would predict two peaks: one at 2 Hz (corresponding to the ocular pulse) and the other at 2.8 Hz (corresponding to the target frequency).

Finally, the sidebands noted by Collins *et al.*[a] around the high frequency peak could be due to amplitude or frequency modulation of the arterial pulse by other physiological rhythms of the cardio-pulmonary system.

In summary, the evidence so far suggests that a high frequency peak in the accommodation fluctuations is due to the influence of the arterial pulse on the accommodation 'plant'. However, there may also be a 2 Hz fluctuation caused by marginal instability of the accommodation system.

Source of Low Frequency Fluctuations

There are three main views on the source of the low frequency fluctuations and these are that the low frequency fluctuations are: an intrinsic part of accommodation control in steady viewing; or due to an instability in the accommodation controller; or due to influences of the cardio-pulmonary system on the eye.

It has been hypothesised that low frequency fluctuations (<0.6 Hz) are used to maintain the steady state response of accommodation,[17,56] and thus are due to neural control. Evidence for this hypothesis comes from the finding that the magnitude of the low frequency fluctuations of accommodation increase when the depth of focus is increased (or when the system becomes more open-loop) by viewing through small pupils[43,45,65] in low luminance,[66] or when viewing empty fields.[41] No one has yet attempted to determine how the characteristics of these low frequency 'accommodation correction cycles'[17] change with stimulus conditions, and it may be that they

are aperiodic and thus would appear as a wide band of low frequency noise in a power spectrum plot.

Hung *et al.* used their dynamic control model to predict a system instability at about 0.45 Hz, much lower than the 2 Hz instability found and modelled by Stark *et al.*[48,63]

Recently Collins *et al.*[a] have located low frequency peaks (<0.6 Hz) in the accommodation fluctuations that correlate with rhythmic changes in the cardio-pulmonary system. Earlier studies would not have been able to resolve these peaks because they did not sample for a sufficiently long enough time period.[67] An exception to these studies is Westheimer who subjectively sampled accommodation in the dark at 0.1 Hz for about 40 minutes. He found low frequency peaks (< 1/60 Hz) but they were not consistent in location. It is interesting to note that in 1955 Allen had suggested that accommodation could be affected by the cardio-pulmonary system.[42]

Collins *et al.*[a] have noted a component at between 0.2–0.3 Hz in the accommodation fluctuations that correlates with the respiration rate, and this could be due to sinus arrythmia. There are also low frequency peaks (<0.1 Hz) that are common to both the accommodation fluctuations and the instantaneous pulse rate which Collins *et al.* have speculated could be due to slow rhythms in the pulse rate such as the Mayer wave and the Traube Hering wave.

In summary it is possible that active neural control, system instability and cardio-pulmonary factors all play a part in the low frequency components of accommodation, but more research is needed on this topic.

1.2.2.5. SIGNIFICANCE OF THE FLUCTUATIONS OF ACCOMMODATION.

Many authors have considered the possibility that fluctuations of accommodation are somehow involved in the accommodation control process,[17,18,40,43,45,52,53,56,63,65,66,68-72] although some have disagreed,[32,48,62] and there is controversy over the exact roles of the low and high frequency

fluctuations. Charman and Heron have distilled the controversy on this topic into three hypothesised roles for the fluctuations of accommodation:

1. They could be an intrinsic part of the overall accommodation control system, with characteristics which actively changed according to the observing conditions in order to help to optimize overall accommodation performance.
2. Their characteristics might be effectively independent of the control system but might still be made use of by that system to aid its function.
3. The fluctuations might simply represent an instability, of little functional significance to the overall operation of the accommodation system.[56]

Fluctuations as an Aid to Dynamic Responses of Accommodation

A number of authors have suggested that the fluctuations of accommodation are used to provide directional information to the accommodation system.[40,68,69,71,72] As pointed out by several authors, only the high frequency fluctuations would be quick enough to provide the information needed to make fast accommodation responses to step changes.[44,56] However if the accommodation system was actively using high frequency fluctuations to provide a directional cue, then it would be expected that the amplitude of these fluctuations would increase to compensate for increased depth of focus when viewing through small pupils or in poor luminance,[56] but this is not the case.[45,65,66] Also, the fact that the high frequency peak changes so readily with pulse rate suggests that the high frequency fluctuations are not under active neural control.[52,54] Thus the high frequency fluctuations are unlikely to provide an odd-error accommodation cue due to active neural control according to hypothesis (1) of Charman and Heron.[56] However it is possible that the high frequency fluctuations could be used indirectly (hypothesis (2) of Charman & Heron), as for example in Kotulak and Schor's model.[72] Although this model uses a 2 Hz fluctuation, there is no reason why it could not use other frequencies.

Fluctuations as an Aid to the Steady State Accommodation Response

Several authors have hypothesised that the fluctuations of accommodation could be used to maintain the steady state accommodation response.[17,18,40,56,63,65,66,70]

It is unlikely that the high frequency fluctuations of accommodation are an intrinsic component of the accommodation control system in steady vision.[56] This is because they do not increase in magnitude to compensate for increased depth of focus as would be predicted when viewing through small pupils or in poor luminance.[17,45,56,65,66] On the other hand, low frequency fluctuations do increase when depth of focus is increased,[45,65,66] and it has been hypothesised that they are involved in accommodation control.[17,56]

The high frequency fluctuations, while probably not under active neural control, may be used indirectly by the accommodation system. For example, 2 Hz fluctuations were found to improve steady state accuracy in one dynamic control model.[63] If high frequency fluctuations are involved in accommodation control, then the temporal changes in supra-threshold retinal image modulation that they produce would be easily detected.[73]

Campbell and colleagues found that the high frequency peak present with a 7 mm pupil disappeared when viewing through a 1 mm pupil,[45] a finding which has been difficult to explain,[43] although Stark and colleagues claimed that their control model could explain this finding.[48] Other studies have failed to replicate Campbell's finding,[65,74] and this issue is investigated further in this thesis (see Chapter 4).

The above discussions on the ability of fluctuations to aid dynamic and steady state accommodation responses relate to the normal accommodation responses to blur with normal cues present. If cues to the direction of the response are reduced, subjects can use voluntary fluctuations of accommodation as a trial-and-error mechanism to find a correct focus.[71] Using this method, responses to step targets are generally slow and erratic.

Summary

Neither the high or low frequency fluctuations are under active neural control to provide a direction cue to the accommodation system, although the high frequency fluctuations could be used indirectly as an odd-error cue. The low frequency fluctuations, but not the high frequency fluctuations, may be under active neural control to maintain the steady accommodation response. Both low and high frequencies could be used indirectly to maintain the steady accommodation response. Some high frequency fluctuations may be due to instability in the accommodation system, while others are caused by the ocular pulse. Some of the low frequency fluctuations are likely to be due to physiological rhythms in the cardio-pulmonary system.

1.2.2.6. FACTORS THAT INFLUENCE FLUCTUATIONS OF ACCOMMODATION

A number of factors in the fluctuations of accommodation have been researched: target form;[50,75-77] target luminance;[40,66] viewing in empty or dark fields;[41,44,68,78] pupil size;[43,45,48,65] monocular versus binocular viewing;[39,49] astigmatism;[37,38] drugs (timolol, betaxalol, phenylephrine);[54,79,80] visual tasks;[81] and age.[49] Some of these factors are more fully discussed in later sections of this chapter.

1.2.3. Responses to Dynamic Targets

The ability of the accommodation system to follow a target moving in depth has been investigated with a number of different target motions: steps, pulses, sinusoidal motion, and ramps. Early studies of the dynamics of accommodation did not measure accommodation objectively (see Allen for a review[82]). A problem with these studies was the errors introduced by hand reaction times. Other studies overcame this error with tachistoscopic presentation methods.[83-85] Continuously recording infra-red optometers and dynamic Purkinje image photography have made it possible to carefully analyse the dynamic accommodation response.

1.2.3.1. STEP STIMULI

The accommodation response to a sudden change in target distance shows two characteristic portions: an initial *reaction period* during which the response does not change, followed by a *movement period* where there is a change in accommodation to the new level. The terms used to describe these various portions of the step response vary from author to author, but the ones I will use are *reaction period* and *movement period* shown by their respective times for execution in the following mnemonic:

reaction time + movement time = total response time

Reaction Period

Typical values for the reaction time to non-predictable target steps range between 280 ms and 425 ms.[42,86-92] Reaction times are independent of the starting accommodation level and direction of a step response,[90] and are independent of monocular or binocular viewing.[92] Reaction times vary between subjects and also vary from trial to trial for a given subject.[89,90,93] Phillips *et al.* noted that frequency distributions of reaction times for single subjects were often skewed.[89]

The reaction time of the accommodation response represents the time required for neural conduction in the afferent and efferent neural pathways, time for central neural processing, and the reaction time of the ciliary body. Thompson found a latency of 80–150 ms to direct electrical stimulation in the ciliary body of the macaque (*Macaca mulata*) and, assuming similar latencies in the human ciliary body, apportioned 100–200 ms for human central accommodation processing.[94] A model of Myers and Stark yields slightly longer latencies than Thompson.[95]

Reaction times for predictable target steps are smaller than those for non-predictable target steps, indicating the influence of anticipation.[87,89] Typical mean reaction times for predictable target steps range between 180 ms and 390 ms.[87,89,93] A remarkable example of anticipation is the occasional *negative* reaction time recorded for some subjects in Phillips and other's study.[89] This prediction possibly operates best for targets cycling at between 0.1 Hz and

0.7 Hz.[89] The presence of negative reaction times is evidence for voluntary intervention in the accommodation response.

Movement Period

The response to a step change in target position usually has an approximately exponential form.[90] Actually, the response is probably not truly exponential because it is known that the accommodation control system is not linear.[48] Also, some step responses are not accomplished in a single sweep: instead the subject makes two or more smaller steps separated by short pauses to assess the blur.[86,91] Sometimes subjects react erratically to target steps or not at all,[91] especially if the target only contains high spatial frequency detail.[96] Nevertheless, where the responses are exponential they can be described by a *time constant*. The time constant is the time required for the response to reach 63% of its final value. Typical values of the time constant range between 225 ms and 440 ms,[86,87,90] although these values depend on the accommodation operating range (near or far) and the direction of the response (see later discussion on range non-linearities).[90] Typical values for the movement time are 640 ms for far to near responses and 560 ms for near to far responses for a 2 D change in target position.[86]

Some studies have reported *total response times* for the accommodation step response (i.e. reaction time + movement time), and typical values range between 560 ms and 2 s.[86,91,92]

There are differences in the dynamic step response depending on the direction of the response, the size of the step, and whether accommodation is operating at a low level or a high level. Some studies have found that an accommodation response going from far to near is faster than one going from near to far,[91,92,94] although the opposite has also been found.[86,87,97,98] A possible reason for these differences can be found in the study of Shirachi *et al.*[90] They found that when accommodation operates in its far range (i.e. closer to the far point) a response in the near direction is faster than one in the far direction. However when accommodation operates in its near range, a response in the near direction is slower than one in the far direction. These differences were attributed to changes in the accommodation 'plant'.[90] When

the lens is stretched flat in the far-seeing accommodation state, it would be more difficult to flatten it further for a far response than to relax tension on the lens for a near response. Similarly when the lens is very rounded in the near-seeing accommodation state, it would be more difficult to induce greater rounding for a near response than to flatten the lens for a far response. In contrast to Shirachi *et al.*, Thompson found accommodation dynamics were independent of the initial response level.[94]

The velocity of the accommodation response is higher for larger steps, and peak velocities can reach values up to 17 $D.s^{-1}$.[86,90,99] Shirachi *et al.* studied the velocity characteristics of the step response.[90] Following the reaction time there is an initial sharp rise in response velocity, followed by a maximum velocity in the middle of the response, and a decrease as the final response level is approached. For a fixed step size and far to near responses, the maximum velocity of the response is higher when accommodation operates in the far range than in the near range. However for near to far responses of a fixed step size, the maximum velocity is independent of the accommodation operating range.

Studies of the effect of step size on accommodation velocity are conflicting. Kasai *et al.* found that the early portions of far to near responses have a constant velocity of about 4 $D.s^{-1}$ and a constant maximum velocity regardless of the amplitude of the step. However for near to far responses, the maximum velocity increases with the step size.[98] In contrast, Shirachi found for far to near responses that the maximum velocity is proportional to the step amplitude for steps smaller than 3 D, but the maximum velocity reaches a limit for steps greater than 3 D. The finding was similar for near to far responses but the limit was 2 D instead of 3 D.

1.2.3.2. FREQUENCY RESPONSE CHARACTERISTICS: SINGLE AND MULTIPLE SINUSOIDAL STIMULI

Sinusoidal stimuli have been used to investigate the accommodation response because if the accommodation system is a linear system then the responses to sinusoids can completely describe the system behaviour for any

target motion. The response of a linear system to a sinusoidal input is also a sinusoid that varies only in amplitude and phase from the input (see Appendix by Zames in Stark *et al.*[48]).

Stark *et al.* demonstrated that for large sinusoidal inputs, the gain and phase lag of the accommodation system fall off monotonically with increasing target frequency.[48] This characteristic has been found in many studies.[64,86,87,100-103] However, in addition, for sinusoids of small amplitudes Stark *et al.* found an increase in gain at about 2 Hz which they attributed to a marginal instability of the system.[48] Sun *et al.* have been unable to replicate this 2 Hz instability.[64]

For low frequencies, the response amplitude closely matches the amplitude of the target motion, and in some cases may actually exceed the amplitude of the input (i.e. gain > 1).[100] Tracking ability is very poor for stimulus frequencies greater than 2 Hz,[100] and is probably non-existent for stimulus frequencies greater than 4 Hz.[86]

Responses to sinusoidal target motion are rarely uniform, they vary from trial to trial, and even over a few seconds in the same trial.[101] Careful instruction is required to minimise response variability.[101] Responses to sinusoids also show steps, possibly indicating dual mode behaviour in the accommodation system[104] (see section 1.2.3.4).

Prediction probably plays a role in the responses to sinusoidal stimuli.[100,101] Response gain is higher and phase lags are lower for predictable versus unpredictable target motion.

1.2.3.3. PULSE STIMULI

Impulse stimuli have been used to determine whether accommodation is a continuously monitoring system. The response to an impulse stimulus is only as long as the length of the impulse, suggesting continuous monitoring by the accommodation system.[86] Sun and Stark supported Campbell and Westheimer,[86] but along with Hung and Ciuffreda they found evidence for dual-mode behaviour in the accommodation system (see 'Ramp Stimuli' below).[99,104]

1.2.3.4. RAMP STIMULI

Campbell and Westheimer noted that the responses to a ramp stimulus were not smooth; there were errors, and subjects occasionally 'lost' the target and focused at some intermediate response level.[86] The ramp appeared to be tracked in steps but it was not possible to definitively demonstrate this because of superimposed fluctuations of accommodation.

Two recent studies have demonstrated dual mode behaviour in the accommodation response to ramps.[99,104] Hung and Ciuffreda showed that the response to slow ramps is predominated by slow *ramp movements*, while the response to fast ramps is predominated by *steps*. These steps appeared to be pre-programmed because the amplitudes of the steps were such that the response was close to the stimulus level at the end of the step.[99] Also the step amplitudes increased with increasing ramp speed. In contrast, Sun and Stark found steps of a constant magnitude of 0.7 D.[104] They modelled this behaviour using a control model with a switching element and a high feed-forward gain. This model accurately predicts an increasing frequency of step responses for faster ramps, however it does not include continuously monitoring feedback.

1.2.4. Tonic Accommodation

The results of numerous studies have shown that in the absence of a visual stimulus to accommodation the eye adopts an intermediate position of focus.[105] Consequently the *intermediate resting hypothesis* states that the resting position of accommodation is not the farpoint but an intermediate focus position.[106,107] Helmholtz is often cited as representing the classical view, however his comment that 'in the passive, far seeing state of the eye the lens is stretched by the zonule attached to its edge', is unfairly taken out of context.[108]

1.2.4.1. TYPICAL VALUES OF TONIC ACCOMMODATION

The resting level of accommodation in the dark for young people has a typical mean value of about 1.5 D, but individual values can range from about 0 D to 4 D.[109]

1.2.4.2. TONIC ACCOMMODATION STATES

As the various visual stimuli to accommodation are degraded, accommodation moves closer to its tonic state. For example, if the detail of a target is made more blurry then accommodation becomes more inaccurate, eventually reaching a fixed tonic level.[9] This behaviour is also observed for small pupils,[17] decreasing target luminance,[11,29] low spatial frequency detail,[12,24] and poor contrast,[110,111] among others. As pointed out by Heath, dark conditions are not necessary for people to adopt a tonic accommodation level.[9]

Various conditions have been used to induce a tonic accommodation state, and these include: dark fields,[105,106] empty fields,[41,78,106] viewing through small pupils,[112] and viewing low spatial frequency targets.[113] Leibowitz and Owens found significant correlations between dark focus, night myopia, empty field focus and instrument myopia.[106]

Monkeys also exhibit a dark focus, and their tonic accommodation level increases during normal sleep and anaesthesia, but moves toward zero as death approaches (*Macaca irus, Macaca speciosa, Cercopithecus aethiops*).[114]

1.2.4.3. SOURCES OF TONIC ACCOMMODATION

Spherical aberration has been hypothesised as a cause of the myopic shift in refraction with low luminances.[115] In degraded stimulus conditions the Purkinje shift in the wavelength of maximum sensitivity with lower luminances has been hypothesised to explain part of the tonic 'accommodation' observed in these conditions (up to 0.4 D).[116]

The tonic accommodation level has been hypothesised to represent a balance between sympathetic and parasympathetic innervation to the ciliary body.[26] Studies with various drugs indicate that there is sympathetic

innervation to the ciliary body which can affect accommodation, but it is not known exactly how much the sympathetic inputs contribute to tonic accommodation.[105,117]

Proximal accommodation[118-120] and cognitive factors[121,122] can lead to changes in the measured tonic accommodation level.

1.2.4.4. STABILITY OF TONIC ACCOMMODATION

The dark focus can vary widely in the short term if subjects remain in the dark.[123] Generally though, tonic accommodation is quite stable over a day,[123,124] weeks[124-126] and even over the period of a year.[127]

1.2.4.5. PROXIMAL AND COGNITIVE FACTORS IN TONIC ACCOMMODATION

The way in which tonic accommodation is measured can contaminate the measured values. Some subjects show higher tonic levels with Badal laser optometers than with infra-red optometers,[118,124] possibly because the laser spot appears to be at a close distance or due to mental effort. Mental effort affects the tonic accommodation level.[121,122] If subjects are aware of the length of an experimental laboratory, then small rooms can induce higher tonic accommodation levels.[119] In contrast, the use of a closed or open instrument may not affect tonic accommodation.[128] Accommodation measures made with small pupils cannot be considered representative of the tonic accommodation level if there are proximal stimuli available because the small pupils do not remove proximal stimuli to accommodation.[120]

1.2.4.6. TONIC ADAPTATION OF ACCOMMODATION

If a subject views a near target and their accommodation is suddenly made open-loop (e.g. by viewing through a small pupil), then accommodation will slowly decay back towards the resting level of accommodation.[129-133] The longer a near target is viewed before accommodation is made open-loop, the slower is the return to the resting level.[134]

The method of opening the accommodation loop affects the rate of decay of accommodation towards the final resting level. The decay of tonic

accommodation is fastest in darkness, slower in empty field viewing and slower still when viewing through a small pupil.[129,130] Bullimore and Gilmartin noted that the rates of decay of tonic accommodation in dark and light fields differ between individuals.[135] Viewing in a dark field masks tonic accommodation that becomes manifest in a light field.[130]

Although Krishnan and Stark noted no effects of instructions on the rate of decay of tonic adaptation, Malmstrom and Randle found that 'thinking near' or 'thinking far' affected the rate of decay.[28,136]

Tonic accommodation increases when measured at regular intervals during a reading task at a close distance.[137] Also, within about 15 to 60 seconds of first viewing a near target, tonic adaptation of accommodation begins to reduce the lag of accommodation leading to a more accurate response.[130] The stimulus–response function intercept (but not the slope) increases following a near task.[23] Schor *et al.* have hypothesised that with sustained near viewing the initial responses of phasic components of the accommodation control system are gradually replaced by tonic adaptation.[138,139]

Researchers differ on whether[139] or not[140] convergence accommodation and accommodation convergence can influence tonic accommodation and tonic vergence respectively.

1.2.5. Voluntary Accommodation

Voluntary accommodation is 'the ability to consciously control the start, amplitude and direction of a change in refraction totally independent, if necessary, of any external stimulus.'[129] However there are other factors such as attention and concentration which probably affect accommodation responses but are not 'voluntary accommodation' in the strictest sense of the definition. These have received little attention elsewhere in the literature.

1.2.5.1. TYPES OF VOLUNTARY ACCOMMODATION

Voluntary accommodation has become an umbrella term for a number of quite different accommodation strategies and so this review will attempt to delineate these various forms of voluntary accommodation.

Absence of Voluntary Accommodation:

First of all I will consider a situation in which voluntary accommodation is *not* involved. Although the accommodation system is known to respond in a reflex manner to the blur of an object (see section 1.4.1), in most instances the intrusion of voluntary accommodation cannot be ruled out. However Kotulak and Schor have demonstrated that accommodation can respond to changes in target position that are small enough to be perceptually invisible.[141] In this situation it is obvious that accommodation acts as a true reflex.

The 'Reflex' Accommodation Response

Fergus Campbell in one of his lectures made the following comment on the so-called 'reflex' response of accommodation:

> I have intentionally avoided the term reflex in this lecture, as it is a word with physiological and psychological overtones which could mislead one into believing that the accommodation reactions were as automatic and involuntary as the pupil reflex; which is certainly not the case.[142]

Accommodation does not generally act as a true reflex and it seems that *attention* is necessary for accommodation to respond to a particular target. For example, if we change our attention from a distant scene to a book at a close distance then accommodation follows along without any conscious effort on our part. We make a *conscious* change in attention, which in one sense may be considered voluntary, but the actual accommodation change is not voluntarily effected. Attention has been mentioned as a factor in accommodation,[103,143,144] but there is little research on the topic.

Researchers studying accommodation in infants have had to make sure they captured the infants' attention,[145] especially with distant targets because infants preferentially attend to near objects.[146] Francis and colleagues used

the term *effort to see* to describe the normal attention given to an object of regard.[147] However it is uncertain from their study whether subjects, when instructed to 'space out', relaxed their attention to a target or used voluntary accommodation to focus away from the target.

The role of voluntary accommodation in the 'reflex' accommodation response can be inferred from studies that have compared voluntary and 'reflex' responses. In the earliest of these, Campbell and Westheimer compared voluntary accommodation excursions made in a dark field to normal responses made to real targets,[86] and claimed that the two types of responses were similar.

Phillips devised a clever experiment to show the importance of voluntary accommodation to step changes in accommodation.[129] Phillips had his subjects focus back and forward on command between two fine line targets separated by 4 D. After several cycles one target was removed without the subject's awareness, and the subject was again requested to focus the now non-existent target. The early responses to a non-existent target were very similar to the 'reflex' responses to the target; that is, the subjects accommodated before they realised that the target was not present. Phillips noted that 'the subjects were not aware that they had specifically voluntary [sic] accommodated but were attentive to keeping a specific target in focus.'[129] Later, Ciuffreda and Kruger compared voluntary excursions of accommodation with responses to real targets, and found that the dynamics of both responses are very similar.[148] They suggested that voluntary accommodation may be a pre-programmed response that is served by similar neural pathways as the 'reflex' accommodation response.

In summary, attention or voluntary accommodation is involved in the so-called 'reflex' accommodation response even though there may be no direct voluntary efforts to alter accommodation. The intrusion of voluntary accommodation in supposedly 'reflex' responses is a major issue particularly as it relates to the possible voluntary accommodation introduced by subject instructions (sections 1.5.1.1 & 1.5.8.1) and predictable target motion (section 1.2.3.2).

Extra Effort to Focus a Target

In some cases subjects do more than simply pay attention to an object of regard; they make an effort to carefully concentrate on its detail.

Trial-and-Error Hunting Responses

A more active voluntary process occurs when subjects exert voluntary effort to hunt for the best focus position of a target.[12,71,149,150] Using a trial-and-error method they voluntarily increase and decrease their accommodation in an effort to find the clearest focus position for a target. As well as visual feedback, subjects may use proprioceptive sensations to estimate their accommodation level (see section 1.2.5.5).[150] Although strenuous, this task is similar to normal tasks because the aim is to see the target clearly.

Voluntary Accommodation Excursions in Empty Fields

Many studies have either demonstrated or tested voluntary accommodation ability by having subjects make voluntary excursions of focus in a dark or empty field, or when viewing a target through a small pupil (open-loop conditions). In some studies subjects were allowed to respond by any magnitude in any direction,[148] while in others they were either to perform positive voluntary accommodation,[151] or to reduce their accommodation level.[152] In other studies, subjects were instructed to use visual imagery to look as near or as far as possible.[41,128,136,153,154] In all these cases the subjects were required to make a voluntary excursion of focus but they were to do this without visual feedback. They would therefore need to rely on proprioceptive cues.

Voluntary Accommodation Away from a Viewed Target

A difficult task (for the untrained) is to make a voluntary change in accommodation away from a viewed target. This is probably because the target blur provides a conflicting stimulus, and also possibly because it takes practice to fixate a target but not pay it attention. In some studies subjects were allowed to respond by any magnitude and in any direction.[86,129,148,155] In Marg's study the direction of accommodation was specified, but subjects

were allowed to respond by any magnitude.[143] In one study, subjects viewed a target but were to imagine it as near or as far as possible.[154]

Voluntary Accommodation to a Remembered Position in an Empty Field

In this type of task subjects must rely on proprioceptive cues to guide their accommodation responses, but there is the additional constraint that they maintain a specified and remembered level of accommodation which increases the level of difficulty. As a practical example, a pilot may need to maintain a distant focus in an empty blue sky to look for other aircraft. Randle found that trained subjects could obtain a focus close to infinity (0.35 D on average) in an empty field, while untrained subjects could not perform this task.[156] Randle found similar results in a later study, but in this case the subjects were aided by auditory feedback.[155]

Gnadt trained Rhesus monkeys to make voluntary near responses in the dark to remembered target positions although he does not state how accurate the monkeys were.[157] Fincham found that many subjects accommodated poorly for the distance of their upheld finger in a dark room even though proprioceptive cues are present in this situation.[158]

Voluntary Accommodation Away from a Viewed Target to a Remembered Position

A difficult voluntary task is to maintain a specified and remembered focus position in the presence of other conflicting targets.[155,156,159] The subject can use proprioception and also the blurring of the conflicting targets as a cue, but must contend with the conflicting accommodation stimuli provided by the conflicting targets. In Roscoe and Couchman's study and one of Randle's studies the subjects' task was made less difficult by the provision of auditory feedback.[155,159]

1.2.5.2. PREDICTION

The ability to predict the response to a periodically or smoothly moving target probably has voluntary components. However changing target size (looming) can also aid in prediction,[160,161] so prediction may not be a purely voluntary phenomenon. Prediction can become marked for static targets, or

for steps and sinusoids of known amplitude and frequency, and has been a problem for researchers attempting to investigate the 'reflex' response of accommodation to blur.[87,89,100,101,162] Nevertheless, it has been suggested that prediction may be important in familiar work environments.[148]

1.2.5.3. ACCURACY AND TIME COURSE OF VOLUNTARY ACCOMMODATION

The accuracy and dynamics of voluntary accommodation vary widely depending on the type of voluntary task. Normal attention for the task or trial-and-error hunting movements can yield accurate responses.[147,150]

When subjects are instructed to look as near or as far as possible in open-loop conditions, shifts of accommodation in the required direction tend to be small,[41,128,154] slow to achieve a final level[154] or transient.[41]

Malmstrom and Randle found that their naive subjects could not shift accommodation away from a fixated target by thinking near or far.[154]

When attempting to attain a remembered distal focus position in open-loop viewing, Randle found that his trained subjects could focus close to their far points (0.35 D accommodation on average) while untrained subjects could not perform this task.[156]

When attempting to maintain a remembered focus position in the presence of other conflicting targets, trained subjects perform quite well at maintaining their 'remembered' focus position, but holding a near focus in the presence of a distant conflicting target is more difficult than the opposite configuration.[156]

1.2.5.4. PREVALENCE OF VOLUNTARY ABILITY IN NAIVE POPULATIONS, INDIVIDUAL DIFFERENCES, AND THE BENEFITS OF TRAINING

Prevalence of Voluntary Accommodation Ability in Naive Populations

Marg, in an informal poll of 50 optometry students, found that about half claimed to be able to voluntarily accommodate after a little practice.[143] Some naive subjects claim to have possessed voluntary accommodation ability since childhood,[163,164] and some studies note that naive subjects vary in their ability to perform voluntary focusing tasks.[143,156] Naive subjects perform

differently depending on the difficulty of the task. For example, Malmstrom and Randle found that naive subjects could effect changes in accommodation by imagining an open-loop target as near or as far as possible, but they could not do this if the target was viewed normally (closed-loop condition).

Training of Voluntary Accommodation

Numerous studies have demonstrated improved voluntary performance with practice[149,165-167] or following training.[151,155,156,159,168,169] Some studies have shown that functional myopes can learn to relax accommodation voluntarily,[155,170] although further research is needed before the technique can be considered useful in reducing myopia.[171]

Once learnt, voluntary accommodation ability may be retained for long time periods: 10 days in Randle's study and 7 years in Trachtman's study.[156,172]

1.2.5.5. CUES TO VOLUNTARY ACCOMMODATION

Proprioception

It is common for subjects to report proprioceptive sensations related to voluntary accommodation.[50,150,156,163-165,173] Some subjects use these sensations to aid their accommodation response,[50,150,165] and when subjects are required to make voluntary accommodation changes in dark or empty fields then proprioceptive cues are the only ones available. The source of these sensations is unknown, and the accuracy of proprioception as a cue to voluntary accommodation is not known.

Visual and Non-Visual Cues

Cornsweet and Crane trained subjects in voluntary accommodation using a variety of methods (auditory feedback, vernier display feedback) and made the point that, if necessary, the accommodation system could probably use *any* cue that provided suitable direction information.[168]

1.2.5.6. PROXIMAL ACCOMMODATION AND ITS RELATIONSHIP TO VOLUNTARY ACCOMMODATION

When subjects make voluntary accommodation changes, do they do this by imagining a near or far object? For example, McLin and Schor, based on the reports of some of their subjects, speculated that voluntary accommodation may be caused by using visual imagery to produce proximal accommodation.[167] All four of Provine and Enoch's subjects stated they were trying to imagine near or far distances, but both of Cornsweet and Crane's subjects denied using imagined distance to produce voluntary accommodation.[151,168] Research on this question is difficult because many subjects who can voluntarily accommodate are unable to verbalise their actions.[151,167]

1.2.5.7. VOLUNTARY ACCOMMODATION AND VOLUNTARY CONVERGENCE

Although the existence of voluntary accommodation is well established, it could be argued that voluntary accommodation actually results from voluntary convergence via the well known convergence accommodation cross-link. In favour of true voluntary accommodation, some early case studies demonstrated that subjects could voluntarily alter their accommodation independent of convergence.[163-165] More recently it has been shown in humans and in trained Rhesus monkeys that the relationship between voluntary accommodation and convergence is closer to the AC/A ratio than the CA/C ratio, indicating that voluntary effort primarily drives accommodation, and then convergence secondarily via the accommodation-convergence cross-link.[157,167] Also, smooth muscle (such as in the ciliary body) can be placed under voluntary control.[174]

1.3. Anatomy and Physiology of Accommodation

Present knowledge of the accommodative neural pathways in humans, monkeys and cats is very scattered. More is known about the ciliary body and crystalline lens, although the mechanism of accommodation has always been a controversial topic.

1.3.1. Retina and Afferent Neural Pathways

The retinal image is sampled by the cones (but possibly not the rods) to provide blur information to the accommodation system.[175] A proposed chromatic mechanism of accommodation control relies on colour opponent information initially sampled from the retinal cones.[176,177] Blur information from the retina is possibly sent via the lateral geniculate body to the primary visual cortex and then on to parieto–occipital areas, although there are other possible pathways, and none have been verified.[178]

1.3.2. Neural Processing

1.3.2.1. CORTICAL AREAS

Present knowledge of the central pathways of accommodation is incomplete. A blur signal from the primary visual cortex possibly passes to the parieto–occipital cortex. Stimulation of these areas in the monkey (surrounding the superior temporal sulcus)[179] and in the cat (lateral suprasylvian area)[178] lead to changes in accommodation, convergence and pupil size. There is a case report of poor accommodation following a haematoma in the parieto–occipital cortex in a human subject.[180] Some cells in the lateral suprasylvian area of the cat are sensitive to motion in depth and size changes, possibly indicating neural processing of proximal stimuli to accommodation.[178,181,182]

1.3.2.2. CEREBELLUM

The cerebellum can influence accommodation in humans,[183] Rhesus monkeys,[184] and cats[185,186] but its exact role is not yet known.

1.3.2.3. MIDBRAIN

In the cat there are connections between the lateral suprasylvian area and the pretectum and superior colliculus.[187] Areas in the midbrain of the cat and monkey (e.g. midbrain reticular formation) may relay information from higher centres to the oculomotor nucleus.[188-191] Cells in the Edinger–Westphal nucleus mediate accommodation signals from higher neural centres to be relayed to the ciliary body.[192,193]

1.3.3. Efferent Neural Pathways

1.3.3.1. PARASYMPATHETIC INNERVATION

A parasympathetic motor signal is sent by the cells of the Edinger–Westphal nucleus via the oculomotor nerve, the ciliary ganglion, and then the short ciliary nerves to the ciliary body.[192] There is probably a synapse in the ciliary ganglion,[192,194,195] although not all agree.[191,196] The innervation of the ciliary muscle takes the form of a wide plexus, so that all regions of the ciliary body are innervated equally.[197]

1.3.3.2. SYMPATHETIC INNERVATION

The pathways and source of sympathetic innervation to accommodation is not known. Sympathetic innervation to the ciliary muscle is: possibly mediated by inhibitory receptors (β2); has only small inhibitory effects on accommodation; is relatively slow; and also depends on concurrent levels of parasympathetic innervation.[117,198,199]

1.3.4. The Accommodation Apparatus

1.3.4.1. CILIARY BODY, ZONULAR APPARATUS AND CRYSTALLINE LENS

According to the Helmholtz–Fincham model of accommodation, in near vision a contraction of the ciliary muscle leads to a reduction in the diameter of the ciliary body.[1] This change in ciliary ring diameter is transferred by the zonular fibres to the crystalline lens which adopts a more curved shape.

Ciliary Body. The ciliary muscle of the ciliary body is multi–unit smooth muscle,[200] and this reflects the need of the ciliary muscle to effect rapid changes in accommodation. The division of ciliary muscle fibres into longitudinal, circular and radial groups may be too rigid: instead most of the muscle fibres may originate at the corneo-scleral spur and have a single action in moving the ciliary body forward and inward on contraction.[201]

Zonules. The zonular fibres transmit forces from the ciliary body to the crystalline lens, but there is controversy over their structure and actions.[201-204]

Crystalline Lens. When the eye accommodates the equatorial diameter of the lens decreases, the central anterior surface becomes more curved, the posterior surface becomes only slightly more curved, the anterior surface moves anteriorly in the eye and the lens thickness increases.[1]

1.3.4.2. THEORIES OF THE MECHANISM OF ACCOMMODATION

Early Theories

Scheiner and Young demonstrated that accommodation in humans is an active process,[205,206] with Young demonstrating that accommodation is not mediated by changes in corneal curvature.[206] Kepler proposed that the lens changes its position in accommodation;[207] however to obtain the full accommodation amplitude would require impossible anterior displacements of the lens. Theories that changes in the length of the globe are responsible for accommodation were refuted by Young,[206] and later by ultrasound measurements of axial length.[208]

Descartes' theory that accommodation is mediated by changes in the crystalline lens would ultimately prove correct.[209] Langenbeck and Helmholtz, using the Purkinje–Sanson reflexes, demonstrated that the anterior surface of the lens becomes more curved in accommodation while the posterior surface becomes only slightly more curved.[210,211] The total lack of accommodation in aphakic eyes was demonstrated by Young and Donders, showing that changes in the crystalline lens are necessary for accommodation.[206,212]

Although the Helmholtz-Fincham model of accommodation[1] is now widely accepted, there have been other lenticular theories for the mechanism of accommodation. Cramer suggested that the contraction of the ciliary muscle increases the vitreous pressure and pushes the lens anterior surface forward through the pupil, resulting in an increase in anterior lens curvature.[213] Cramer's theory was refuted by Graefe who demonstrated full accommodation in an aniridic patient.[214] An early theory of Tscherning's held that in accommodation for near vision, increased tension in the zonules flattens the peripheral portions of the lens, moulding the lens cortex over the

more steeply curved nucleus.[215] Tscherning formed a second theory relying on the work of Pflugk: the Tscherning–Pflugk theory.[216] In this theory, ciliary muscle contraction leads to increased vitreous pressure which pushes against the posterior lens surface. But as the lens is prevented from moving forward by the action of the zonules, the anterior lens surface is forced to assume a more curved shape. A Hydraulic Theory proposed by Hill suggests that the contracting ciliary muscle places pressure on the aqueous in the posterior chamber which in turn compresses the peripheral portion of the lens causing the central anterior surface to bulge through the pupil.[217] However this mechanism is unlikely as young aniridic eyes can still accommodate.[214]

Helmholtz-Fincham Model

According to Helmholtz's theory of accommodation, in near vision contraction of the ciliary body causes a reduction in the tension of the zonules which allow the crystalline lens to adopt a more curved shape.[108] Gullstrand elaborated on Helmoltz's theory, adding the theory of an elastic lens capsule that moulds the crystalline lens substance.[218] Fincham further expanded on the role of the elastic capsule in moulding the lens substance. In his theory, the central anterior surface of the lens adopts a more curved shape than the peripheral anterior surface because the capsule is thinner in the central region.[1,219] However Koretz and Handelman's mathematical model suggests that the capsular force acts evenly over the lens surface.[220]

Other Recent Theories

Coleman's theory attempts to unite the Helmholtz–Fincham and Cramer, Tscherning-Pflugk theories by emphasising the role of the vitreous in providing support for the posterior lens surface.[221] Schachar has recently hypothesised that an increase in zonular tension is needed for near vision.[222-224]

1.4. Stimuli to Accommodation

There has been considerable controversy regarding the stimulus or stimuli used by the accommodation system to obtain its response. A stimulus to accommodation has been defined as 'visual information used to effect predictable changes in the accommodation response, resulting in improved retinal-image quality and consequent reduction in accommodative error.'[15] Defocus blur is considered to be the primary stimulus to accommodation, but a problem with un-aberrated dioptric blur is that it only provides an *even-error* cue; that is, it does not provide any information on the *direction* of the correct response. The aberrations of the eye, however, have the potential to provide *odd-error* cues: that is, they provide a cue to the direction of the required response. Many other cues to the correct response direction have been proposed. In addition to defocus blur and its associated cues, *perceived distance* can also provide a direct stimulus to the near response. The relative importance of defocus blur (retinotopic) and perceived distance (spatiotopic) stimuli,[144] is considered in a later section (see section 1.4.3).

1.4.1. Blur

Defocus blur along with associated cues to the direction of the accommodation response can initiate *reflex* accommodation responses. There has been controversy over whether blur itself can act as a stimulus to accommodation. To study this question researchers have compared responses to a change in stimulus vergence (i.e. *defocus blur*) versus a change in target clarity (i.e. *target blur*). Fincham had his subjects view a target pattern projected on a screen while he altered the focus of the projector (i.e. target blur), and noted that none of the subjects made any response to this blurred image.[32] From this Fincham concluded that 'differences in definition' of a target are not a stimulus to accommodation. Smithline also found poor responses to target blur.[225] However a problem in both these studies is that if subjects had made a response to the blurriness of the target, this would have further increased the blur of the target (i.e. now a combination of target blur and defocus blur) and so inhibited an accommodation response. This

deficiency was remedied by Phillips and Stark by feeding the subject's response level to the projector focus mechanism so that when subjects responded in the correct direction they were rewarded by a reduction in blur.[71] This study demonstrated that subjects can respond to target blur alone, although the responses are slow and erratic, and subjects use hunting movements to obtain a correct response. This is in contrast to the quick responses for defocus blur. Thus, while accommodation can respond to blur alone, it is likely that other cues are used to direct the response during normal viewing.

1.4.1.1. CHARACTERISTICS OF BLUR USED AS A STIMULUS

If we are correctly focused on a target then the amplitude of target contrast and also the gradient of this contrast are maximal, however, with defocus, the contrast gradient falls off more rapidly than the contrast amplitude. Fujii *et al.* suggested that the contrast gradient is used for fine adjustments of focus while the contrast amplitude may be used when the blur is large.[226]

1.4.1.2. CUES TO THE CORRECT RESPONSE DIRECTION

Chromatic Cues

The human eye suffers about 2 D of chromatic aberration between 400–700 nm,[116,227] and as the eye has three types of cone receptors tuned to different regions of the visible spectrum, it is possible that the outputs of these receptors could be exploited to provide directional information to the accommodation system.[70,228] Fincham investigated whether chromatic aberration acts as a cue to the correct direction of the accommodation response.[32] In white light all 55 of his subjects made a response in the correct direction upon the insertion of a negative lens in their line of sight. However when chromatic aberration was removed by viewing in monochromatic light or viewing through a lens to correct the eye's chromatic aberration, 35% of these subjects made no accommodation response, 25% made a partial response, and 40% made a normal response. This study demonstrated that

for many subjects chromatic aberration is an important cue to accommodation.

Since Fincham's study in 1951 researchers have disagreed on whether chromatic aberration does act as a cue to accommodation. Using a hand tracking task, Campbell and Westheimer found that all 4 of their subjects could respond correctly in monochromatic light,[229] however Stark and Takahashi demonstrated that initial hand tracking responses are random in direction whether the target is illuminated by white or monochromatic light.[230] Two studies found that the use of monochromatic light or of lenses to neutralise, double or reverse the eye's chromatic aberration has no effect on the ability of subjects to accommodate to steady targets.[149,231] Accommodation is poor to isoluminant colour contours, suggesting to some researchers that chromatic cues may not be involved in accommodation control.[232,233]

In contrast to the previous studies, Kruger and colleagues have demonstrated that accommodation responses to dynamic targets are impaired in monochromatic light or when the chromatic aberration of the eye is neutralised, and that this sensitivity to chromatic cues is widespread.[176,234-238] The finding of Charman and Tucker that subjects did not initially respond reflexly to step changes in the monochromatic colour of a target support the findings of Kruger and colleagues,[149] however van der Wildt *et al.* found no difference between responses to dynamic white and monochromatic targets.[101] Kruger and colleagues reasoned that voluntary accommodation may prevent chromatic effects being observed for steady targets, and also that the poor responses to isoluminant colour contours are due to a disruption of the colour fringes around a target that are normally used as an accommodation cue. Accommodation can still respond to achromatic targets, but this achromatic mechanism is less sensitive and slower than the chromatic mechanism.[176]

It has been speculated that colour opponent channels may mediate information on the direction and magnitude of the required accommodation response.[228,239] Evidence for this hypothesis comes from a clever experiment

by Kruger and colleagues.[177] They had subjects view a stationary 'white grating' under open-loop conditions, and then *simulated* the changes in modulation in the red, green and blue components of the grating that would normally result from dioptric defocus. On average subjects accommodated quite well to this stimulus.

Spherical Aberration

Fincham investigated the possibility that spherical aberration may be used as a cue to accommodation, but in a few subjects found that it did not affect the accommodation response.[32] In contrast Campbell and Westheimer found that subjects could not always respond in the correct direction in a hand tracking task when chromatic and spherical aberration were absent, although they could when spherical aberration was present.[229] A mechanism by which spherical aberration could be used as a cue has not been described. Spherical aberration varies in both sign and magnitude with the level of accommodation,[240,241] and it is difficult to see how accommodation could use a cue that varies so much.

Astigmatism

A few authors have suggested that astigmatism may be used as a cue to accommodation,[42,229] but this possibility has not been adequately researched.

Fluctuations of Accommodation

The possible role of fluctuations in accommodation control is discussed in a previous section (see section 1.2.2.5). Neither the high or low frequency fluctuations are under active neural control to provide a direction cue to the accommodation system, although the high frequency fluctuations could be used indirectly as an odd-error cue. The low frequency fluctuations, but not the high frequency fluctuations, may be under active neural control to maintain the steady accommodation response. Both low and high frequencies could be used indirectly to maintain the steady accommodation response.

Scanning Eye Movements and the Stiles-Crawford Effect

Fincham noted that small scanning eye movements (approximately 6 minutes arc or greater) were necessary for an accommodation response to occur and suggested that these movements could be coupled with the Stiles-Crawford effect to provide a directional cue to accommodation.[32]

Other Cues

A number of researchers have pointed out that subjects can learn to use almost any cue that provides directional information.[162,168,230] Some of these potential cues are: auditory cues;[42] focus dependent shifts in the phase of a target;[60] predictable target motion;[162] lateral target movement;[162] and changes in target luminance and size.[162]

1.4.2. Perceived Distance

In many situations perceived distance can act as a direct stimulus to accommodation. Although there are many cues to distance (see for e.g. Ogle[242]), few of these have been directly investigated for their potential to act as stimuli to accommodation.

1.4.2.1. PERCEIVED DEPTH IS A STIMULUS TO ACCOMMODATION

If care is taken to remove conflicting blur stimuli (by viewing through a small pupil to greatly increase the depth of focus of the eye) then it is possible to demonstrate steady proximal accommodation responses to steady targets. Plots of the proximally induced responses as a function of the dioptric target distance are linear with typical slope values of 0.32–0.6 D/D,[120,121,243,244] although Hennessy *et al.* found a low value of about 0.1 D/D.[245] The proximal response to a steady target distance can be maintained for over 5 minutes.[244] These results obtained while subjects used the depth cues available in normal laboratories show that perceived depth acts as a true *stimulus* to accommodation, and not simply as a direction cue.

1.4.2.2. DOES PERCEIVED DISTANCE STIMULATE ACCOMMODATION DIRECTLY?

Perceived depth can induce changes in both accommodation and vergence, and as there are links between accommodation and vergence (i.e. accommodation-convergence and convergence-accommodation) it is uncertain how perceived depth influences this interactive near response. Rosenfield and Gilmartin used the term *proximally induced accommodation* rather than *proximal accommodation* because the former does not imply that perceived distance stimulates accommodation directly and exclusively.[243]

Studies of this question are contradictory. For example, while Wick and Bedell concluded that perceived distance affects accommodation through the convergence accommodation cross-link, McLin *et al.* concluded that (for most of their subjects) size changes affect accommodation primarily and vergence secondarily through accommodation convergence.[161,246] Later Wick and Currie concluded that perceived distance stimulates both accommodation and convergence directly.[247]

1.4.2.3. PERCEPTUAL CUES TO DEPTH AND THEIR ABILITY TO STIMULATE ACCOMMODATION

Relative Size. Varying the size of a familiar object such as a playing card can (in the absence of other cues) lead to changes in perceived distance via size-distance constancy,[248] and thus might stimulate changes in vergence and accommodation. A problem with many of the studies on this topic is that accommodation was left closed-loop, and so if proximity had led to a change in accommodation then this would have blurred the target resulting in a compensatory response to the blur. In closed-loop viewing, relative size either did not affect accommodation,[249,250] resulted in small changes in accommodation,[251] or led to brisk dynamic changes in accommodation.[229]

Changing Size (Looming). A target moving in depth provides a dynamic cue to accommodation via size-distance constancy. An early study of Ittelson and Ames found small changes in closed-loop accommodation due to a looming cue,[251] however in closed-loop viewing blur will tend to suppress any proximally induced accommodation changes.

In open-loop accommodation, looming acts as a stimulus to accommodation over a similar temporal frequency range to that for blur driven accommodation.[160,161,252] The accommodative gain varies between subjects for a target whose size changes sinusoidally with time.[252] The responses to sinusoidally changing size show phase *leads* over the low and mid temporal frequencies: that is, the responses lead the size changes.[160,161,252] Several reasons have been proposed for the phase leads to looming (compared with normal phase lags to blur stimulation). It is possible that the accommodation system responds to the rate of change of size rather than size per se.[161,252] It is also possible that the phase leads are due to anticipation or a predictor operator.[161,252]

Ciuffreda noted that accommodation becomes more accurate as the size of a target increases (up to about 3–4°) and that this is a possible contaminating factor in studies of the effect of looming on accommodation.[15]

The addition of looming cues to blur cues does not seem to affect the accommodative gain but it does reduce the phase lag.[160,161,234] The interactions between size and blur stimuli are probably non-linear.[253]

Stereoacuity. In a reduced blur cue situation, stereograms can induce changes in both perceived depth and accommodation.[254]

Motion Parallax. Takeda *et al.* found that motion parallax cues in a specially designed moving random dot pattern induced small changes in closed-loop accommodation.[255]

Body Proprioceptive Information. Fincham found that subjects were unable to accommodate correctly to the distance of their upheld finger in a completely dark room.[158]

Pictorial Depth Cues. Closed-loop accommodation responses can be affected by pictorial distance cues in paintings.[255]

Multiple Depth Cues in Real and Artificial Scenes. Morgan used the cues of overlap, relative size and luminance to provide true or incorrect cues to depth and found that these cues did not affect closed-loop accommodation.[256] Hofstetter and Alpern separately, using targets in real

space, also found no evidence of proximal effects in closed-loop viewing.[257,258] As previously noted, closed-loop viewing inhibits proximal accommodation. Nevertheless, Gwiazda and colleagues have found subjects who accommodate poorly to the blur produced by interposed trial lenses when viewing targets in real space.[259,260]

The differences in sensitivity to distance cues reported in various studies[120,121,243-245] may be due to the effectiveness of the multiple depth cues available in laboratories and outside scenes. Also, some people are more sensitive to proximal cues than others.[261]

1.4.3. Relative Importance of the Various Stimuli to Accommodation

The various stimuli to accommodation have different operating ranges, and operate most effectively in different situations.

1.4.3.1. OPERATING RANGES FOR BLUR STIMULI

Very small amounts of blur are unable to stimulate accommodation due to the *accommodative depth of focus*. Blur also fails to stimulate accommodation if it is greater than the *accommodative upper blur threshold*, generally considered to be about ±2 D,[32] but see the discussion later in this section. It is important to note that the accommodative depth of focus and accommodative upper blur threshold can be different from their perceptual counterparts.

Accommodative Depth of Focus: the Lower Blur Threshold

Kotulak and Schor demonstrated that accommodation can respond to changes in target distance smaller than the perceptual depth of focus.[141] However their study could only determine the accommodative depth of focus for one subject because for the others their apparatus was unable to produce sinusoidal target motion smaller than 0.12 D in amplitude. Ludlam *et al.* found step responses to target changes of just 0.1 D,[262] although they did not attempt to determine a threshold.

Research is needed to determine the accommodative depth of focus for a range of pupil sizes, and to compare these values to perceptual depths of focus at various levels of defocus. It is known that the perceptual depth of

focus is minimal at levels of defocus either side of the optimal focus position.[60,263] Also, accommodation is usually inaccurate and may operate near these points of minimum perceptual depth of focus. It may be that the minimum perceptual depth of focus and accommodative depth of focus are not too different.

Upper Blur Threshold

Fincham had his subjects view a distant target, and noted their accommodation responses on the interposition of negative lenses.[32] He observed 'reflex' responses to blur of less than about 2 D, and also that above this value 'the response is no longer involuntary'. At the other extreme of blur levels, Provine and Enoch found that young subjects did not initially accommodate to 9 D blur induced by a negative power soft contact lens.[151] Although these studies suggest the presence of an upper blur threshold, a confounding factor is that conflicting distance and blur cues were present. Subjects may have failed to respond to large blur levels because they knew they were looking at a distant target.

An upper blur threshold has been considered by some authors and appears in some control models of accommodation,[48,104,144] but there has been little research on the topic. Tucker and Charman have determined the perceptual upper blur threshold for a range of spatial frequencies and luminances, however their subjects' accommodation responses to the same gratings may not indicate accommodative upper blur thresholds because of voluntary accommodation.[264]

It is obvious that an upper blur threshold will depend on the spatial frequency content of a target. For example, a very fine grating target with only high spatial frequency content will quickly become invisible with defocus. Tucker and Charman have argued that any spatial detail of a target that is sub-threshold due to blur cannot be used to drive accommodation.[13,264,265] In particular, the high spatial frequencies are more susceptible to blur than the low spatial frequencies. (See Figures 8 & 9 of Tucker *et al.* for theoretical and experimental determinations of the modulation threshold as a function of spatial frequency.[266]) Some subjects in

Charman and Heron's study demonstrate this effect: they could accommodate to step changes in the stimulus levels of low and mid spatial frequency gratings but not high spatial frequency gratings.[96] Bour found inadequate responses to 1 D and 1.5 D steps of a 16 cycle.degree^{-1} grating when the grating contrast was lower than 20%.[50]

It would probably be difficult to measure an upper blur threshold due to the intrusion of voluntary accommodation. For example, Phillips suggested that the initial part of a 'reflex' accommodation response is probably voluntary in nature.[129] Voluntary accommodation could be used to overcome a *blur* threshold.[264] Also, the ability to predict target motion could be used to obtain a good response in the face of large amounts of blur.[50] If proximal stimuli are available then these may be used to overcome large amounts of blur.[144]

1.4.3.2. OPERATING RANGES OF PERCEPTUAL STIMULI TO DEPTH

Schor *et al.* have considered the operating ranges of the various proximal stimuli to accommodation in detail.[144] Static perceptual cues operate for large distance separations. Cues such as overlap only provide direction information, while size-distance constancy can provide information on both the direction and magnitude of the required accommodation change. Although the model of Schor *et al.* limits looming cues to small amplitudes (<0.5 D),[144] it is possible that accommodation may respond to looming at higher levels of defocus.

1.4.3.3. RELATIVE IMPORTANCE OF BLUR AND PERCEIVED DISTANCE

The operating ranges just described provide an idea of when the different stimuli to accommodation are most active. In addition to these operating ranges it is important to consider how the various stimuli and cues interact.

When the blur system is closed-loop (as it is in most real situations) *conflicting* proximal stimuli have little if any effect on accommodation,[249,251,256-258] although some studies have found a significant effect of proximal cues.[259,260] In addition, Hung *et al.* have recently predicted

that when blur and proximal stimuli *agree*, proximal accommodation contributes very little to the *steady* accommodation response.[267] When the blur stimuli to accommodation are reduced or if the system becomes more open-loop (e.g. small pupils, low spatial frequency target) then proximal stimuli become more prominent. Some people are more sensitive than others to proximal stimuli.[261] For dynamic stimuli, the addition of a size stimulus to the blur stimulus reduces the phase lag of accommodation but does not seem to improve gain.[160,161,234]

1.5. Factors in the Accommodation Response

1.5.1. Spatial Frequency, Contrast and Target Form

1.5.1.1. SPATIAL FREQUENCY

This section reviews studies of accommodation to single sinusoidal grating targets, while accommodation to more complex targets is considered in a later section.

Spatial Frequency and the Accuracy of Accommodation

Various studies on the spatial frequency dependence of accommodation have conflicted with each other, and so Ciuffreda and Hokoda grouped these studies on the basis of four patterns of accommodation accuracy as a function of spatial frequency.[150] (1) If sinusoidal gratings were ineffective stimuli to accommodation, then accommodation would adopt a level close to its resting level. (2) According to the *fine focus control* hypothesis, accommodation becomes progressively more accurate for higher spatial frequencies targets, provided that the targets are still visible.[12,13]
(3) According to the *contrast control* hypothesis, mid spatial frequencies provide the best stimulus to accommodation.[24,50,77,103,129] The optimal spatial frequency found by these latter studies lies in the range 3–6 cycles.degree^{-1} but may be as high as 7 cycles.degree^{-1}. (4) Finally, the *spatial frequency independence* hypothesis states that accommodation accuracy is independent of spatial frequency.

Ciuffreda and Hokoda noted that individuals can be found that fit any of the above response patterns, except the spatial frequency independence hypothesis.[268] Also, in another study they noted marked effects of instruction on the spatial frequency response pattern.[150] For example, when a subject was instructed to 'relax' while viewing the grating, the response pattern fitted the contrast control hypothesis, but with the instruction to 'try very hard to keep the grating at the maximal high contrast level' the response pattern fitted the spatial frequency independence hypothesis. Owens had previously suggested that the differences between his study (using the instruction 'focus all targets naturally, without straining') and that of Charman and Tucker may have been due to voluntary accommodation induced by Charman and Tucker's instruction to 'always try to obtain the best possible focus.'[24] Thus, the intrusion of voluntary accommodation makes it difficult to determine the characteristics of the 'reflex' response to blur alone.

Another factor in these studies is the ability of subjects to predict the target stimulus level. Apart from randomising the presentation of steady targets, two studies have used dynamic targets to reduce target prediction.[50,103] Both of these studies support the contrast control hypothesis of accommodation, and thus it is likely that the 'reflex' response to blur is most accurate for intermediate spatial frequencies in the range 3–6 cycles.degree^{-1}. The accommodation cue provided by chromatic aberration is most sensitive to spatial frequencies in the 3–5 cycles.degree^{-1} range.[269]

Spatial Frequency and Accommodation Fluctuations

The experimental results relating to this topic are conflicting.[50,75-77] Denieul *et al.* found a minimum in fluctuations for a 7 cycles.degree^{-1} grating, but a minimum in the ratio of high frequency to low frequency activity (HF/LF) at 3 cycles.degree^{-1}.[77] In contrast, Ujike and Ikeda's data shows little variation in the accommodation fluctuations with spatial frequency.[76]

Spatial Frequency and Accommodation Dynamics

Responses to both steps and temporal sinusoids are most accurate for intermediate spatial frequencies, and in the case of temporal sinusoids, accommodation is most accurate for mid-spatial frequency gratings regardless of temporal frequency over a wide range.[50,103] Step responses for high spatial frequency gratings can be poor or absent,[96] possibly due to an upper blur threshold.

1.5.1.2. CONTRAST

Contrast and the Accuracy of Accommodation

Accommodation is very robust to changes in target contrast, but returns to its resting level when contrasts falls below some threshold value. This threshold has been termed the *accommodation response contrast threshold* by Ward.[111] For contrast levels above the accommodation contrast threshold, accommodation either remains accurate or starts to decline slowly towards the resting level as contrast is reduced.[13,50,110,111,266] Accommodation is most robust to changes in contrast of the mid spatial frequencies present in a target, and least robust to reductions in the contrast of high and low spatial frequencies.[113,129] Values of the accommodation contrast threshold vary with spatial frequency and between individuals, but values of 0.03–8% Michelson contrast have been cited by Ciuffreda and Rumpf,[110] and values of up to 26% have been cited by Ward for high spatial frequency targets.[111]

Fujii *et al.* proposed that the contrast gradient of a target is important for fine control of accommodation, while the contrast amplitude may be used when the initial blur level is large.[226] This hypothesis has received support from a number of studies.[110,270]

Contrast and the Fluctuations of Accommodation

Spectral power of the accommodation fluctuations may increase for low contrasts, but only for low spatial frequencies.[76]

Contrast and Accommodation Dynamics

The study of Bour shows a small decline in accommodation accuracy to step stimuli as target contrast is reduced, with a failure of accommodation once the accommodation contrast threshold is passed.[50]

1.5.1.3. COMPLEX AND NATURAL TARGETS

Compound Sinusoidal Targets

The responses to sums of sinusoids provides information on how the various spatial frequency components of a target influence the final accommodation response. They also provide a bridge between the sinusoidal targets of the research laboratory and the complex targets found in the real world.

Charman, Tucker and colleagues have argued that in normal viewing, low spatial frequency information provides the initial drive to accommodation and progressively higher spatial frequencies are used to refine the response as they rise above threshold.[13,264,265] This has been called the fine focus hypothesis. However the superior responses to mid spatial frequencies for single sinusoids suggest that accommodation may not use high spatial frequency detail, and this is the basis of the contrast control hypothesis.

In support of the fine focus hypothesis, responses to square gratings (< 1–2 cycles.degree^{-1}) are more accurate than sinusoidal gratings of the same frequency.[110,129] Also, some studies have shown an improvement in accommodation accuracy as odd-harmonics are added to a base sinusoid to yield a target pattern progressively more like a square grating in appearance.[77,265,271]

Dul *et al.* found that accommodation accuracy only improved with the *successive addition* of odd harmonic components of a square wave grating to the base sinusoid: accommodation was poor to a combination of high and low frequency components (in opposition to the fine focus hypothesis), and accommodation was also poor for mid spatial frequency components only (in opposition to the contrast control hypothesis).[270] Dul *et al.* concluded that the main factor in accommodation accuracy was whether the addition of

higher frequency components improved the *sharpness* of the grating detail, in accord with the contrast gradient hypothesis of Fujii *et al.*[226,270] Nevertheless, the successive odd harmonic components required by the contrast gradient hypothesis will only be available if they are above threshold, in other words, if these components are initially too blurred then it is the low spatial frequency components that will initially drive the response, as argued by Charman and Tucker.[13,265]

For spatial frequencies greater than about 2–4 cycles.degree^{-1}, accommodation responses to sinusoidal and square gratings of the same frequency are almost identical.[110,129,271]

The difference of Gaussians target has a narrow band of spatial frequency content and has been used by Kotulak and Schor to assess accommodation accuracy as a function of the target's centre frequency.[113] With this target accommodation is more accurate for a combination of mid to high spatial frequencies than for a combination of low to mid spatial frequencies.

Natural Targets

Ciuffreda *et al.* found accurate accommodation responses for a wide variety of reading material of various spatial frequency and contrast composition, although their experiment might have been more sensitive if the target stimulus level was higher and more removed from the subjects' average resting level of accommodation.[272] Blurring of letter targets leads to a reduction in accommodation accuracy,[9,273] probably due to the loss of high spatial frequency information.

Letter Size and Accommodation. Letters are common objects in every-day tasks and are also used in accommodation research. Some studies have found no effect of letter size on accommodation,[12,16,274,275] while others have found effects of letter size[68,276] which are small (<0.25 D).[276] It should be noted that only one study has measured accommodation responses over the whole accommodation range, and then for only one subject.[12] Also, the effect of letter size will depend on the accommodation strategy of the subject, which in turn may depend on the instructions given to the subject. For example,

some subjects may always try to obtain maximum clarity and probably would not show an effect of letter size.[12] Other subjects may accommodate only enough to make the letters legible, and thus would show more accurate responses for small letters.[12]

1.5.2. Temporal Characteristics of the Target

This section deals with the effect of temporal variations in target detail on the accommodation response. The effect of temporal variation in the stimulus level of a target has previously been discussed (section 1.2.3.2).

1.5.2.1. FLICKERING TARGETS

Flicker in the range 1–300 Hz has been investigated for its effect on accommodation, with studies differing in their findings. Owens and Wolfe found that accommodation accuracy for mid spatial frequencies was unaffected by flicker (3–40 Hz), but responses for high and low spatial frequency gratings became poorer with low frequency flicker.[277] Neary found an increased accommodation response at all stimulus levels for lower frequency flicker (25-50 Hz) compared with higher frequencies of flicker.[278] Charman and Chauhan noted a marked reduction in the accommodation stimulus–response slope for some subjects when the target flickered at a frequency near their critical fusion frequency.[279]

1.5.2.2. LATERAL TARGET MOTION

Ciuffreda, Kellndorfer and Rumpf found that accommodation was slightly more accurate for a slowly drifting grating (0.1 degree.s^{-1}, equivalent to 0.4 Hz) than for a stationary grating.[280] Accommodation became poorer with increasing target velocity, approaching the resting level for a velocity of about 6 degree.s^{-1}. Flitcroft found that a 4 cycles.$degree^{-1}$ grating drifting at 4.2 Hz (equivalent to 1 degree.s^{-1}) was best able to *initiate* an accommodation response.[281] The differences in these studies may be due to the different processes involved in initiating and maintaining an accommodation

response. Hung *et al.* demonstrated a reduction in accommodation accuracy as the velocity of a laterally oscillating target was increased.[282]

1.5.3. Target Luminance

1.5.3.1. LUMINANCE AND RESPONSE ACCURACY

Several studies have shown a reduction of accommodation accuracy at low luminance levels,[11,29,175] but accommodation accuracy does not seem to be affected too greatly for luminances higher than about 5–10 $cd.m^{-2}$. [11,29] As luminance is reduced, the stimulus–response function slope eventually falls to zero, and the dark focus position is adopted.[29] Nadell and Knoll did not find an effect of target luminance,[283] but this may have been because their subjects viewed a distant target which probably was not too distant from their resting levels of accommodation.

Alpern and David reported their results in terms of retinal illuminance which is useful because in the real world the pupil size increases as target luminance is lowered, and retinal illuminance takes both of these factors into account.[11] Accommodation accuracy decreases as illuminance decreases over the 10–1000 troland range, and there is a dramatic reduction in accuracy for retinal illuminances lower than about 1 troland.* Also the accommodation near point recedes and the accommodation far point approaches as retinal illuminance decreases.

Alpern and David noted that the reduction in accommodation accuracy in low luminances is probably not due to luminance per se, but rather is due to the reduction in contrast of the target against its background.[11] (Similar results were found when a dark target was viewed on a light background through neutral density filters, or when a light target was viewed on a completely dark field through the filters). Tucker and Charman showed that the dioptric range over which a target is visible shrinks as luminance is decreased.[264] This effect is most marked for the high spatial frequencies, and so with wide spatial frequency band targets, accommodation becomes poor

* A retinal illuminance of 1 troland is obtained when viewing a target with a luminance of 1 cd/m^2 through a 1 mm^2 pupil.

with decreasing luminance because of the unavailability of high spatial frequency information. Kotulak and Schor, using difference of Gaussians targets of fixed contrast, found that accommodation accuracy decreased more for the high than the low spatial frequency targets as luminance was reduced.[113] In contrast, Tucker and Charman, using sinusoidal gratings of fixed contrast, found no change in accommodation accuracy as luminance was reduced, provided the grating was still visible.[264] The differences between these two studies may be due to voluntary accommodation induced by the subject instructions.

1.5.3.2. LUMINANCE AND FLUCTUATIONS OF ACCOMMODATION

Accommodation responses become more variable at very low luminance levels.[40,66] Gray *et al.* have shown that the increased variability of accommodation at low luminances is due to low frequency temporal changes in accommodation: the high frequency components are independent of luminance level.[66]

1.5.4. Peripheral Target Detail

In every-day viewing, there are usually objects in both our central and peripheral fields of view. If these objects are at different distances then they have the potential to affect accommodation.

1.5.4.1. INFERENTIAL CONTRIBUTIONS

Toates thought that if accommodation was limited to centrally viewed targets then this would prevent unwanted responses to conflicting targets:

> The eye in general views a scene consisting of objects located at various distances. It is possible for only some of these to be in focus at any given time and the object to which attention is directed will be imaged at the central fovea. It would therefore be a hindrance if the defocus that will inevitably occur outside this region were able to influence the response.[26]

Gu and Legge cited clinical experience that accommodation is still present in young persons with central field defects.[284] Luria and Kinney found that stereoacuity of underwater divers was affected by the size and distance of surrounding peripheral objects, and Hennessy speculated that peripheral objects may lead to an increase in accommodation and a subsequent reduction of stereoacuity due to blur.[250,285]

1.5.4.2. EXPERIMENTAL STUDIES

Early studies suggested that accommodation is limited to a small central region of the visual field. Fincham noted that his subjects made no response to the interposition of a -0.75 D lens when fixating a point greater than 10 minutes arc from a target.[32] Campbell concluded that only foveal cones could drive accommodation.[68,175]

Phillips found that accommodation was fairly sensitive to the eccentricity of an annulus target. Responses to a 3 D target step were poor for target eccentricities greater than 1.5° radius, and absent for eccentricities greater than 10° radius.[129] On the other hand, Gu and Legge found that accommodation was extremely robust to target eccentricity, occurring even for a disc target of 30° radius.[284] Other studies have yielded results between those of Phillips, and Gu and Legge.[15,78,282,286,287] Ciuffreda compared the accommodation stimulus–response function slope as a function of eccentricity for many of these studies (see his Figure 11.32).[15] Possible reasons for the disagreements between studies are discussed below. These studies all agree though that there is a reduction in accommodation accuracy for targets in more peripheral locations in the visual field.

Other studies have investigated the effect of conflicting peripheral targets on the response to a centrally fixated target and these also demonstrated that peripheral targets can influence accommodation (see section 1.8.1.4).[250,288-290]

Recently Ciuffreda and colleagues investigated the effect of target size on steady accommodation.[15,291] They found that as the diameter of a grating target was increased, accommodation became more accurate up to about 3° or 4° radius, after which further increases in target size did not improve

accommodation accuracy. Furthermore, similar results were obtained even without the central 0.5° radius of target detail. These findings suggest 'pooling of cone responses to synthesise the initial accommodation-related neural signal'[15] and suggest that peripheral portions of a target contribute to accommodation accuracy.

Little is known of the dynamics of accommodation to peripheral targets, although Semmlow and Tinor's study suggests that accommodation to peripheral targets may be slower.[286]

1.5.4.3. FACTORS IN THE RESPONSE TO PERIPHERAL TARGETS

Some factors may explain the variability between studies of the accommodation response to peripheral targets.

Blur and or Proximal Stimuli to Accommodation

It is important to consider what stimuli were available to subjects in various studies. For example, some studies have used Badal systems to reduce the proximal stimuli to accommodation.[78,129,250,282,286,287,289] In other studies there have been concordant[288,290] or conflicting[32,284] blur and proximal stimuli. In some studies the experimental set-ups represent real world situations, but in others the mixture of blur and proximal stimuli is an impediment to interpreting the responses to conflicting targets.

Target Size and Spatial Content

It is possible that there is pooling of cone responses to the accommodation system[15] so, as suggested by Miege, small discontinuous targets in the peripheral field of view would probably have less effect on accommodation than larger targets.[289] Peripheral targets with more detail have greater influences on accommodation.[250] The spatial frequencies present in a target must also be considered in relation to the changes in visual acuity, depth of focus and contrast sensitivity with retinal eccentricity (see below). Many studies have used annulus type targets and it would be anticipated that as eccentricity increases, accommodation uses progressively lower spatial frequencies from the wide band of available frequencies.

Attention, Subject Instructions and Voluntary Accommodation

Phillips noted that subjects had to concentrate on peripheral targets to keep them focused, while responses to central targets were more reflex in nature.[129] Although attending to peripheral targets is a difficult task, no studies have yet investigated the effect of attention on accommodation to peripheral targets. It is possible that a cognitively demanding and centrally viewed task may bias attention and prevent accommodation to peripheral objects.

Ciuffreda noted that instructions to subjects can influence the response to peripheral targets: responses tend to be more robust against target eccentricity with an 'active' instruction than with a 'passive' instruction.[15]

The practice effects shown by Phillips' subject suggest that voluntary accommodation may be important in the response, although the improvements shown by this subject could be due to an improved ability to redirect attention to the peripheral target.[129] If subjects are given time they may use voluntary accommodation to focus for a steady peripheral target, and this has been considered a possible reason for the robustness of accommodation to target eccentricity found by Gu and Legge.[15,284]

All studies on accommodation to peripheral targets to date have either used steady targets or predictable dynamic targets. It is therefore difficult to determine how accommodation responds to the blur stimuli of peripheral targets because the amount of voluntary effort or prediction ability is not known.

Individual Differences

Semmlow and Tinor noted that one of their four subjects made no responses to non-foveal targets,[286] and so there may be individual differences in sensitivity to peripheral targets.

1.5.4.4. THEORIES OF REDUCED ACCOMMODATION RESPONSES TO PERIPHERAL TARGETS

Some studies have suggested that accommodation is limited to a very small central region of the visual field. If this were the case then it may be

explained on a simple anatomical basis; only information from the central visual field is sampled by the neural accommodation control centres. However not enough is known of the neural anatomy of accommodation pathways to either support or argue against this hypothesis. Furthermore, no studies have yet tried to isolate blur driven accommodation responses to peripheral targets from proximal and voluntary influences.

Theories based on Peripheral Acuity and Depth of Focus

Visual acuity plotted as a Snellen fraction decreases rapidly with eccentricity for photopic conditions, although plotted as the minimum angle of resolution there is a roughly linear decline with eccentricity.[292-295] Although the eye has significant amounts of peripheral astigmatism and field curvature, the limiting factor to peripheral acuity is the neural organisation of the retina and visual pathways.[296] Contrast sensitivity to mid and high spatial frequencies reduces in the peripheral field of view.[297,298] There is a reduction in the maximum detectable spatial frequency (the 'cut-off frequency'), and the peak sensitivity shifts towards lower frequencies.

Changes in visual acuity and contrast sensitivity with eccentricity can be explained by retinal scaling reflected in the cortical magnification factor.[298-300] Visual acuity in the central and peripheral retina is equivalent if targets are scaled to provide equivalent neural representations.

Several researchers have attempted to predict accommodation performance based on measures of visual acuity and depth of focus.[17,30,301] An implicit assumption in these models is that the accommodation and geniculo-striate neural pathways are closely related in some way, whether anatomically or functionally. Charman's model starts with the assumption that the eye maintains a retinal blur diameter that is proportional to the difference between the target stimulus level and the accommodation resting level — this is a statement of the proportional control exhibited in steady state accommodation.[30] For pupil sizes greater than 3 mm, Charman predicts that the slope of the stimulus–response function is given by the equation

$$|m| = 1 - c.(MAR),$$

where c is a constant and MAR is the minimum angle of resolution. Applied to peripheral vision, the model predicts poorer accommodation responses in peripheral vision due to larger values of the minimum angle of resolution. Bullimore and Gilmartin obtained a value of $c = 0.17\,\text{min}^{-1}$ from their peripheral accommodation data and the visual acuity data of Wertheim.[292,302]

1.5.5. Target Presentation Method

We most commonly view objects in *real space*. However objects can also be viewed through optical instruments such as microscopes and telescopes. The Badal optical system is commonly used in accommodation research to present targets to subjects. Also, the use of head up displays and virtual reality systems is becoming more common. People can have difficulties focusing correctly when viewing with these instruments.

1.5.5.1. BADAL OPTICAL SYSTEM

The Badal optical system is used widely in accommodation research because targets can be presented to subjects that do not change in size or in luminance with the stimulus level of the target.[303,304] However, both experienced and inexperienced subjects have reported difficulties when attempting to focus targets in Badal optical systems.[18,42,149,155] These subjects can benefit from practice at the task and an explanation of the apparatus.[149,155] Some studies have reported poorer responses to Badal targets than to targets in real space.[86,305] Some people may have difficulties with Badal systems because in the Badal system the depth cues available in real space viewing are absent. Also the nearness of the apparatus to the eye may induce a perception of nearness that conflicts with the optical distance of the target. For example, Fisher and Ciuffreda found that most subjects judge a Badal target to be at a fairly close distance, and that this apparent distance does not vary greatly with the optical stimulus level of the target.[306]

No studies have yet compared the accommodation stimulus–response functions in Badal and real space viewing, so it is unknown whether the

accommodation responses recorded in Badal systems can be validly applied to real space viewing. This question is investigated in Chapter 3.

1.5.5.2. TARGETS IN REAL SPACE VIEWED THROUGH TRIAL LENSES

Some subjects respond poorly to the blur stimuli to accommodation provided by interposed ophthalmic lenses when they are viewing real targets at a known distance.[259,260]

1.5.5.3. VIRTUAL REALITY AND HEAD UP DISPLAYS

Many individuals tend to focus inwards when viewing the information provided by a head up display even though that target detail is imaged at optical infinity.[307,308] Some virtual reality systems also provide a mismatch between accommodation and convergence stimuli which prevents accurate accommodation.[309]

1.5.5.4. INSTRUMENT ACCOMMODATION

Instrument accommodation (or instrument myopia) refers to inaccurate responses of accommodation when viewing through instruments such as microscopes, telescopes, and binoculars. Although many studies have investigated instrument myopia, few have measured accommodation, and fewer still have had a no-instrument control condition (see Wesner and Miller's review[310]).

In studies where accommodation was measured, values of the accommodation level in instrument viewing range up to 4 D,[106,250,311,312] although factors such as the type of instrument, and the instrument settings made by the observers affect the above values. It is possible that true instrument myopia does not exist; that is, accommodation responses may be the same regardless of whether the target is viewed with or without an instrument. A study using night vision goggles supports this idea, although further research is needed with other instruments.[312]

A number of theories have been advanced for the generally myopic accommodation levels adopted in instrument viewing. The first is that

accommodation tends towards the intermediate resting position and this is supported by the positive correlations between instrument accommodation and dark focus.[106,250,312] Hennessy suggested that the small exit pupils of many instruments may allow accommodation to move closer to the resting level.[250] However, while small exit pupils may influence instrument accommodation, they are not a necessary condition for instrument accommodation.[312,313] Another theory with experimental support is that instrument users adjust the instrument focus so that they can accommodate closer to their dark focus where acuity is maximal.[311,312]

Finally, Schober *et al.* [314] suggested that instrument myopia may be due to observers focusing for what they believe is a near object. Hennessy disagreed with Schober, but Hennessy would not have found proximal accommodation in his experiment because subjects viewed targets closed-loop with natural pupils.[250] Kotulak *et al.* found that when viewing through night vision goggles, some subjects respond for the known distance of a target even though the target is imaged at optical infinity.[315] Perceived distance cues may play a role in instrument accommodation.

There is probably no single factor that explains instrument accommodation. Three statistically significant factors have been proposed for at least one instrument (night vision goggles): the individual dark focus, the no-instrument accommodation level, and the amount of focus adjustment made by the user.[312]

1.5.6. Pupil Size

Most studies of the effect of pupil size on accommodation accuracy have found a reduction in the slope of the stimulus–response function with decreasing pupil size. The accommodation response approaches the resting level of accommodation for very small pupils.[17,112,245,316] However Kasai and colleagues found that the stimulus–response slope was independent of pupil size.[27,226] The lag of accommodation increased with smaller pupil sizes and was approximately equal to the depth of focus. There are no apparent reasons for the differences between these studies.

Ward and Charman have modelled the effect of pupil size on static accommodation using geometric optics and assuming that the accommodation system works to maintain a retinal blur circle diameter that is proportional to the difference of the target stimulus from the accommodation resting level — that is, proportional control is active.[17] In contrast, the data of Kasai *et al.* can be modelled without proportional control.[28]

The effect of pupil size on the fluctuations of accommodation is investigated in a later chapter (see chapter 4), and its significance for theories of the role of fluctuations in accommodation control is considered in section 1.2.2.5.

1.5.7. Visual Acuity

If the effect of poor visual acuity is simulated by blurring the detail of a target, then it is found that the slope of the accommodation stimulus–response slope decreases with poorer visual acuity, eventually reaching some constant resting level.[9,273] Accommodation accuracy is generally poorer in amblyopic eyes.[22,268,317,318] Dynamic responses to step targets are slower in amblyopic eyes.[319]

A number of models have been developed that relate accommodation accuracy, visual acuity and the perceptual depth of focus. Green, Banks and colleagues have predicted accommodation responses of infants based on either depth of focus values or visual acuity.[301,320] Charman has developed a model which, if verified, suggests that accommodation may be predicted from the visual acuities obtained when factors such as target blur, luminance, and retinal eccentricity are varied.[30] The poor static accommodation responses in amblyopia have been modelled as a decrease in accommodation controller gain and an increased depth of focus.[318]

1.5.8. Cognitive and Higher Order Effects

1.5.8.1. SUBJECT INSTRUCTIONS

Owens suggested that subject instructions may account for some of the differences observed in studies of the spatial frequency response of accommodation.[12,24,50,129,268] Ciuffreda and Hokoda demonstrated marked effects of instructions on the spatial frequency response pattern in one subject, indicating the importance of voluntary accommodation mediated by instructions to the subject (see section 1.5.1.1).[150] Accommodation accuracy is poorer when subjects are instructed not to pay attention to the target.[147] Accommodation to a distant scene is the same regardless of whether the subject is instructed to look at the scene or to observe it carefully.[321] In summary, most research shows that instructions can have important influences on the steady accommodation response. However, the effects of instructions on accommodation have not been systematically investigated. I investigate the effects of various instructions on steady state accommodation in a later study (Chapter 3).

Responses to step changes in target position are quicker with active than with passive instructions.[322] Dynamic responses to sinusoidal target motion are also affected by subject instructions. Van der Wildt *et al.* obtained the most consistent responses to sinusoidal target motion when subjects were instructed to 'concentrate on the diagram [target]' rather than with the instruction to 'keep the clear vision situation'.[101] Similarly, Mathews *et al.* demonstrated that responses are more noisy with an active 'focus on the target' instruction than with a 'look at the target' instruction, but that the extra activity with the active instruction does not improve the accuracy of accommodation.[103]

Responses to laterally drifting targets are more accurate with an active than with a passive instruction.[280] Also, accommodation responses to peripheral targets are more accurate with an active than with a passive instruction.[15] The dark focus of accommodation is affected by subject instructions,[128] but studies conflict over whether instructions affect the slow drift of accommodation to its resting level in open-loop experiments.[28,136]

1.5.8.2. MENTAL EFFORT AND TASK EFFECTS

If the mental task relates to the target being viewed then responses tend to become more accurate with the mental task.[122,323,324] In contrast, accommodation tends to drift away from a viewed target if the mental task is not related to the target.[325,326] The poorer response in the latter case may be due to a division of attention between the two tasks.[325,326] In open-loop conditions, persons with the lowest responses in passive viewing show the greatest increases in accommodation when performing a related mental task.[122]

1.5.8.3. MOOD

Mood, stress and anger can affect the dark focus of accommodation.[41,327,328]

1.6. The Life History of Accommodation

1.6.1. Development of Accommodation in Infancy

Newborn infants and those up to about 1 month of age either show no response of accommodation or focus accurately for near targets but not to distant targets.[329-331] Accommodation accuracy improves with age, reaching adult levels by between 2 and 6 months.[301,329-332]

1.6.2. Presbyopia

1.6.2.1. TIME COURSE AND CHARACTERISTICS OF PRESBYOPIA

Both the subjective and objective amplitudes of accommodation decrease with age, but the objective amplitude reaches zero by about 50–55 years of age.[10,212,333] Clinical subjective amplitude of accommodation can be higher than the actual amplitude due to the depth of focus of the eye.[10,334] The objective amplitude of accommodation falls off linearly with age (≈ 0.3–0.4 $D.year^{-1}$).[333,335]

The accommodation stimulus–response function slope has been shown to decrease longitudinally with age for one subject, although more research is needed on a larger subject group.[335] Characteristics of the fluctuations of

accommodation may change with age.[49] The reaction time of accommodation to step targets does not change with age, but the response during the movement period begins to slow after 30 years of age.[334] Tonic accommodation decreases slightly with age.[335-337]

1.6.2.2. THEORIES OF THE MECHANISM OF PRESBYOPIA

Numerous theories have been proposed for the loss of accommodation amplitude with age, and these can be divided into lenticular and extra-lenticular theories. Lenticular theories include the Hess–Gullstrand theory,[218] and the theories of Duane and Fincham.[1,338] The Hess–Gullstrand theory proposes that the ciliary muscle force required for a given change in accommodation remains constant with age, while the theories of Duane and Fincham propose that the ciliary muscle force required for a given change in accommodation increases with age. Another lenticular theory proposes that due to changes in the shape of the crystalline lens and the insertions of the zonules in the capsule, the zonules are less able to transmit forces to the lens.[339]

There are a few extra-lenticular theories of presbyopia. Fisher's work contradicts the theory that presbyopia is due to weakening of the ciliary muscle.[340] Another theory proposes that with age the lens adopts a more curved shape because the elastic components of the ciliary body and choroid lose their elasticity,[341] and thus according to this theory presbyopia is the inability to relax accommodation.

1.7. Models of the Accommodation Response

At present the most common approach to modelling the accommodation system is that of control system engineering. However models of accommodation can be as simple as a linear regression fit to the stimulus–response function. No matter how simple or complex, the most important test of any model is provided by a simple question:

Does it work?

If a model does work then its components should also be physiologically justifiable.

1.7.1. Control System Models

The application of control systems engineering to the near response triad was pioneered by Stark and colleagues in the 1950's.[62] Since then many workers have developed control models that describe various aspects of accommodation function. Fundamental to these control models is the concept of negative feedback (see Figure 3 of Krishnan and Stark[28]). If the eye is out of focus for a target then this results in blur which is sensed by the retina and processed by the central nervous system. Signals are sent to the ciliary body and lens which result in an accommodation response to decrease the blur. Thus the accommodation system acts by negative feedback to reduce the blur of an attended target. (See Hung and Ciuffreda's glossary in Schor and Ciuffreda for a description of control engineering terms.[342] This glossary also lists relevant texts, to which can be added Riggs' text.[343])

1.7.1.1. CONTROL SYSTEM MODEL COMPONENTS

The Error Detector. Most models define the blur signal as the algebraic difference between the target stimulus level and the instantaneous accommodation response level. This operation gives both directional and magnitude information and assumes that various cues provide the direction of the required accommodation response. Also, the error detector samples the retinal blur continuously (see section 1.2.3.3). Kotulak and Schor developed an error detector that obtains direction information (an odd error cue) from the small fluctuations of accommodation.[72] Also Flitcroft calculated that colour opponent mechanisms would be able to extract an odd error cue from defocus, but did not propose a formal model of this error detector.[228]

Depth of Focus. Many models include the perceptual depth of focus as a dead space element. This element models the inability of accommodation to respond to very small amounts of blur,[20,28,63,144,344] although there is no established value for the *accommodative* depth of focus (see section 1.4.3.1).

Upper Blur Threshold. A few models include an upper blur threshold which models the inability of eyes to respond 'reflexively' for large amounts of blur (see section 1.4.3.1).[104,144]

Accommodation Controller. The accommodation controller represents the neural processes involved in accommodation control, and there has been controversy over the form of this neural control. Toates argued that the accommodation system exhibits *proportional control* because this type of control explains the 'leads' and 'lags' of accommodation observed when people focus for steady targets.[26,345] However, Toates' model gives a highly oscillatory response following a step change in target motion.[28 fig.7a]

Krishnan and Stark noted that when the accommodation feedback loop is suddenly opened (e.g. by viewing through a small pupil, or in a dark or bright empty field) then accommodation slowly drifts towards its resting level (see section 1.2.4.6).[28] They argued that *proportional*, *integral* and *bang-bang*[346,347] type controllers could not explain this behaviour, and proposed instead the *leaky integrator*. Although Krishnan and Stark argued against proportional control in the accommodation system, Hung and Semmlow demonstrated that a particular form of the leaky integrator could explain the dynamic responses of accommodation, the slow return of accommodation to a resting level in open-loop experiments, as well as the proportional control seen in steady state accommodation responses.[20]

Control models have difficulty modelling the responses of subjects with stimulus–response slopes close to +1. As the gain of the controller is increased the model approaches instability.[63] Hung *et al.* inserted a 2 Hz fluctuation in their model to obtain small improvements in gain without system instability.[63]

Stark *et al.* used a third order system controller with non-linear elements to describe the response of accommodation to small and large amplitude target motions, and although the model performed well, it had an unrealistically small value (100 ms) for the system dead time (see below).[48]

Phasic and Tonic Control. A few control models include elements to describe the fast responses of accommodation (phasic control) and the process of tonic adaptation (tonic control).[140,144,344,348] Some models allow convergence accommodation and accommodation convergence to stimulate tonic accommodation and tonic vergence respectively,[144,348] while others place tonic components before the accommodation and convergence cross-links.[140,344]

Controller and Plant Delays. Delay or *dead time* elements represent the amount of time required for neural processing in the afferent and efferent neural pathways (see section 1.2.3.1). Some models use one dead time element to represent the total reaction time of the accommodation system (about 0.35 s),[26,48,104,144] although one model apportions some of the dead time to the neural control processes and some of the dead time to the ciliary body and lens.[63]

Accommodation-Convergence and Convergence-Accommodation Cross-links. Some models ignore binocular interactions[26,28,48,63,72,104,346] while others include both vergence, accommodation and their interactions.[20,130,138,144,267,344,349]

Tonic Accommodation. Most models include the tonic resting level as a bias element.[20,26,63,104,344]

Plant. The accommodation *plant* (i.e. the ciliary body–zonule–crystalline lens apparatus) is modelled with various degrees of sophistication in various models. Some models ignore the plant.[48,344] Because the plant reacts faster than the neural controllers,[28] some models simply use a unit gain element with a saturation limit to represent the amplitude of accommodation.[20,28] Toates used a non-linear function to represent the plant.[345] Others have modelled the plant as a leaky integrator with a fast time constant,[63,104,144] while O'Neill developed models of the plant based on biomechanical

investigations and electrical stimulation of the accommodation apparatuses in cats.[346,347]

Proximal Accommodation. Two recent models include the effects of both blur and perceived distance on accommodation.[144,267] The model of Hung *et al.* is a steady state model, while the model of Schor *et al.* is dynamic and takes into consideration the operating ranges of the blur (retinotopic) and perceived distance (spatiotopic) stimuli.[144]

1.7.1.2. ACCOMMODATION CHARACTERISTICS NOT PRESENTLY MODELLED

Responses to Multiple Targets. No-one has yet attempted to model the accommodation response to multiple targets, such as occurs for example when viewing a distant scene through a window screen. In a later study I extend the control system models approach currently used for single targets to the case of multiple and conflicting targets (Chapter 8). The models I develop have multiple inputs representing the stimulus levels of the various targets, but only one output which is the accommodation response level.

Responses to Extended and Peripheral Targets. The responses to single peripheral targets have not previously been modelled, even though current control models could be used for this purpose. In a later study I develop a control model with multiple inputs representing the various constituent parts of an extended target (Chapter 5).

1.7.2. Optical Models

Based on geometrical optics and a simple model eye Green *et al.* developed a theoretical equation relating depth of focus, visual acuity and pupil size.[320] They also used modulation transfer functions and a diffraction free, aberration free eye to relate depth of focus to acuity. To relate depth of focus to accommodation accuracy they assumed that infants would focus to bring the target within their depth of focus, and then estimated the maximum and minimum stimulus–response slopes that would result.[301] The actual stimulus–response slopes of both infants and adults fitted the theory quite

well, indicating that accommodation function can be predicted by visual acuity.

Charman,[30] after Ward and Charman,[17] used a geometrical optical model to predict the accommodation stimulus–response slope from a subject's minimum angle of resolution for a particular stimulus configuration. Although several studies show a linear relationship between accommodation stimulus–response slope and minimum angle of resolution, the slopes and intercepts vary between studies.[30] If the parameters of Charman's equation proved to be stable, then it would be possible to predict a person's accommodation response based on their tonic accommodation level and their minimum angle of resolution.

1.8. Conflicting Stimuli to Accommodation

Most research on accommodation has been limited to central viewing of single targets. However in the real world there are usually many objects in the field of view that can provide stimuli to accommodation. Two or more objects may lie close to the line of sight and provide conflicting stimuli to accommodation. Objects may also lie in the peripheral field of view and provide stimuli in opposition to an object viewed centrally.

Due to the chromatic aberration of the eye, objects of different colours can provide conflicting stimuli to accommodation. If the eye is astigmatic then detail of various orientations in the object are imaged at different distances in the eye, providing conflicting stimuli to accommodation.

There may be conflicting stimuli to accommodation when the two eyes have different amounts of uncorrected ametropia, that is, when a person is anisometropic. Asymmetric convergence also leads to small differences in the accommodative stimuli for two corrected eyes.

1.8.1. The Mandelbaum Effect

1.8.1.1. AN ACCOMMODATION PHENOMENON

In 1960 Joseph Mandelbaum published his observations on what he called an 'accommodation phenomenon'.[350] His paper described the inappropriate accommodation response that occurs when viewing a distant scene through a window screen. Mandelbaum first noticed this phenomenon while resident at a hospital in New York:

> Years ago when I was a resident at Bellevue Hospital I observed an interesting phenomenon which, I believe, sheds some light on this problem [the problem of whether accommodation is a true reflex]. As I looked out of my screened bedroom window across the East River, the buildings on the horizon in Brooklyn and Queens became blurred. I could make out only their vague outlines; their most obvious details had disappeared. It occurred to me that I was accommodating on the window screen. I set my entire mind and all my efforts to scrutinize the distant buildings: I was no longer aware of the intervening screen. However, try as I would, I could not bring into focus the distant buildings, even though awareness of the screen seemed to have been dispelled.[350]

Mandelbaum noted that he could overcome the phenomenon by moving his head from side to side, and reasoned that this was because head movement blurred out the detail of the window screen. He also noticed that the effect was most pronounced at an intermediate distance — when he stood close to the screen or further than 10 feet from the screen there was little or no blurring of the distant scene.

Years later Mandelbaum performed an informal experiment on the screen enclosed porch of his summer cottage. His subjects viewed a distant sign through a window screen on the porch. The greatest blur of the distant sign occurred when the screen was 91 cm to 183 cm from the subjects. The phenomenon was not observed by cyclopleged right eyes (cyclopentolate) but could be seen by fellow untreated eyes. Furthermore, phenylephrine left the phenomenon intact. (Phenylephrine causes pupil dilation like

cyclopentolate, but does not greatly affect accommodation). These last two trials demonstrated that the effect truly was an accommodative phenomenon because it did not occur during cycloplegia.

Mandelbaum's 'accommodative phenomenon' has become to be known as the *Mandelbaum effect*. The Mandelbaum effect can be defined as the involuntary shift of accommodation towards a conflicting target away from the normal response for an attended target.

1.8.1.2. POSITION OF FOCUS WITH CONFLICTING TARGETS

Since Mandelbaum's report, several researchers have tried to determine how the eye focuses when it is presented with conflicting targets. Generally, the literature to date shows that the accommodation response to conflicting targets is difficult to predict.

Magnitude of the Mandelbaum Effect

The magnitude of the Mandelbaum effect varies widely from study to study, from subject to subject, and even from trial to trial for the same subject. Some factors which may help to explain these differences are discussed in a later section.

Mandelbaum[350] did not measure accommodation in his study although an estimate can be made of the accommodation changes that occurred. The subjects viewed 5 inch letters at a distance of 85 yards (6/6.74 Snellen equivalent). Assuming that subjects were accommodating accurately to the letters without the interposed screen, then about 0.5 D of unwanted accommodation would be needed to make this letter size unrecognisable.[351]

Owens[166] found accommodation shifts varying between 0.5 D to 1.0 D for various target pair separations (range 0–5 D), although some subjects showed greater accommodation shifts towards the conflicting target. One subject's performance (Subject L.W. of experiment 1) improved with practice, and this suggests she was gaining voluntary control over her accommodation with practice. The Mandelbaum effect appeared to be greatest when the conflicting target was placed near the individual dark focus level.

Benel[352] found accommodation shifts of up to about 1 D with a high contrast conflicting target. Low contrast targets were not able to induce a Mandelbaum effect.

Both Owens (in his second experiment),[166] and Adams and Johnson[353] instructed subjects to 'relax and let your eye choose a target'. Owens found that with this instruction subjects tended to focus the target closest to their individual dark focus level. However Adams and Johnson also found subjects who preferentially focused the nearer of two targets, or the vertical target of a vertical–horizontal pair. Rosenfield and Ciuffreda[354] instructed their subjects to 'fixate a point of intersection of the orthogonally oriented stimuli.' They found that many subjects focused mid-way between two conflicting targets. These three studies show that the variability in individual responses can be as great as the separation of the targets. However, a common feature of these three studies is that the instructions did not give the subjects a definite task to focus one of the two conflicting targets. The variability between subjects may be due to uncertainty, or to shifts in attention from one target to the other.

Collins *et al.*[355] investigated the accommodation response to a visual display terminal with superimposed screen reflections. They only found Mandelbaum effects smaller than 0.25 D and only in monocular viewing. This small effect could be because the screen and the conflicting reflections were separated by only 0.66 D.

In summary, it is difficult to predict exactly how accommodation will react when viewing conflicting targets. With an effort to focus one target, there may be a Mandelbaum effect of up to 1.0 D depending on the target separation, but some people perform significantly worse. Without an effort to focus one particular target, accommodation can vary anywhere between the levels of the conflicting targets, provided they are within the range of accommodation.

Preference for Target Closest to the Tonic Accommodation Level

The clue that the resting state of accommodation may have an important influence on the response to conflicting targets was first provided by

Mandelbaum.[350] He found that a distant sign was most blurred when viewed through a screen at an intermediate distance from the eye.[350] The subjects noted maximal blurring when the screen was between 91 cm and 183 cm from the eye (i.e. 0.5 D to 1.0 D accommodation demand). No blurring was noted when the screen was closer than about 45 cm from the eye (2.25 D), or when it was further than about 2.1 m (0.5 D) from the eye. These observations suggested to Owens that when presented with conflicting targets, accommodation would be biased towards the target closest to the individual resting state of accommodation.[166]

In his first experiment, Owens found (in a sample of 4 subjects) that an interposed screen caused the greatest Mandelbaum effect when it was closest to the individual dark focus.[166] Accommodation to the fixation target was most stable when it was placed at the individual dark focus level. However the findings were not analysed statistically to determine if there was a correlation between the dark focus and the screen distance at which there was the greatest Mandelbaum effect. If it is hypothesised that a screen at the dark focus induces the greatest Mandelbaum effect, then a plot of screen distance for greatest Mandelbaum effect as a function of dark focus should have a slope of +1 and an intercept of zero.

From the studies discussed so far there is evidence to support a relationship between the tonic resting state and the response to conflicting targets; but the evidence is not sufficiently convincing to establish this relationship.

Preference for Positions of Maximum Contrast Gradient

Fujii *et al.*[226] designed an experiment to determine whether the contrast amplitude or the contrast gradient is most important for accommodation control. When presented with two gratings separated by 2 D, subjects found it easier to focus at one or other of the gratings but not in-between the gratings. According to Fujii *et al.* the contrast gradient is maximal when focused for one of the two targets, but the contrast amplitude is maximal between the two targets. This led Fujii *et al.* to conclude that the contrast gradient is used in fine focus control, while the contrast amplitude is used

when there are large errors of focus. Their study suggests that when presented with conflicting targets it is more natural for subjects to focus one target or the other, but not to focus in-between the conflicting targets. Other studies suggest that people do focus between conflicting targets,[353,354] so the evidence is conflicting.

Idiosyncratic, Unexplained or Unpredictable Responses

Adams and Johnson found that some subjects preferred to focus the nearer of two conflicting targets,[353] and they attributed this to proximal accommodation. Adams and Johnson also found two subjects who preferred to focus the vertical target of a vertical–horizontal pair. They considered it possible this may represent a 'learned' or 'habitual' response.

One subject in Owens' first study showed improvements at a conflicting targets task with practice,[166] suggesting that she was learning to use voluntary accommodation to overcome the Mandelbaum effect.

Rosenfield and Ciuffreda found that subjects focused at many different positions between two conflicting targets.[354]

Summary

Rosenfield and Ciuffreda summed up their study with the following statement which I think also summarises the literature to date:

> Under naturalistic viewing conditions, the retinal image is composed from a complex, multilayered object space involving overlapping, spatially disparate object planes, resulting in varying degrees of retinal image defocus. The findings of the present study indicate that the [accommodation response] to this array of multiple stimuli cannot be predicted from the responses to its individual components alone.[354]

1.8.1.3. DYNAMIC ACCOMMODATION WITH CONFLICTING TARGETS

Several investigators have considered whether the accommodation response becomes less stable when viewing conflicting targets. Owens made the qualitative observation that when two conflicting targets straddled the individual dark focus, subjects tended to adjust focus from one target to the

other in a cyclic manner.[166] He suggested this may be caused by shifts in attention from one target to the other.

Adams and Johnson[353] recorded accommodation continuously with an infra-red optometer and stated that 'fluctuations of accommodation were approximately equal for each stimulus separation, and were similar to those found in other studies using single stimuli.' However they did not cite standard deviation values or the results of power spectrum analysis. Rosenfield and Ciuffreda measured accommodation subjectively with a Hartinger optometer and found that the standard deviation of the accommodation responses did not vary with various target separations.[354] Similarly, Collins *et al.* using a Canon Autoref in static shot mode noted that the standard deviation of accommodation responses to the screen of a visual display terminal did not increase when conflicting screen reflections were present.[355]

Thus it appears that accommodation does not become more variable when there are conflicting targets, although no one has investigated the fluctuations of accommodations to date. It is possible that changes in the fluctuations of accommodation would not be detected when calculating a standard deviation.

1.8.1.4. FACTORS IN THE MANDELBAUM EFFECT

Previous research has investigated some of the factors in the Mandelbaum effect. Some of these factors are well established, while others are speculative. In this section I also include speculations of my own that have not previously been considered in the literature.

Tonic Level of Accommodation

As previously mentioned, there is evidence to support a role for the tonic resting state in the response to conflicting targets, but this hypothesised relationship has not yet been formally tested. It is possible that conflicting targets placed at the dark focus induce the greatest shifts in accommodation away from the target of interest.[166,350] Also, if the target of interest is placed

at the individual dark focus then accommodation to this target may be more resistant to conflicting stimuli.[166]

Benel collected data which might have answered the question of whether the dark focus is the position at which a conflicting target can induce the greatest Mandelbaum effect.[352] He measured dark focus levels and accommodation responses to a range of conflicting targets. Unfortunately though, Benel did not provide any details on individual (or mean) dark focus levels, and did not attempt to correlate the dark focus with the conflicting target responses. The averaged group data presented by Benel though does seem to show a higher Mandelbaum effect for intermediate positions of the conflicting target.

Some other studies have presented data on the relationship between tonic accommodation and the responses to conflicting targets.[166,353,354] However, the subject instructions in these studies did not provide the subjects with a definite task to attend to one particular target. The results are therefore confounded by the potential of subjects to focus either target at will.

Subject Instructions and Voluntary Accommodation

Subject Instructions. The instructions given to the subjects and the effects of these instructions on attention and voluntary accommodation may explain some of the variability in subject responses found in previous studies. Subject instructions can have a large influence on the accommodation response, probably acting through voluntary accommodation or higher order control (see section 1.5.8.1).

Several studies have given subjects the definite task of attending to one of two conflicting targets.[166,355] Other studies do not record the instructions they provided to the subjects, although it can be implied that the subjects were required to attend to one target.[290,350,352]

Three studies have provided instructions that may have allowed the subject to attend to either target.[166,353,354] Owens, in his second experiment,[166] and Adams and Johnson[353] instructed their subjects to 'relax and let your eye

choose a target'. While Owens found that his 4 subjects all focused the targets closest to their dark focus, Adams and Johnson found other patterns of responses. Two subjects always focused the nearer of two targets, which was attributed to proximal accommodation. Another two subjects always focused the vertical target, and this was considered possibly a 'learned' or 'habitual' response. However , the instruction to 'relax and let your eye choose a target' may have been ambiguous for some subjects. They may have attended to either target and not known at which one their eye felt most relaxed. For consistency the subjects may have decided to always focus for the vertical target. The observations of Owens using the same subject instruction support the possibility of voluntary shifts of attention between the targets. Owens noted that when two targets straddled the dark focus, subjects tended to focus back and forward from one target to another in a cyclic manner.[166]

Rosenfield and Ciuffreda[354] instructed their subjects to 'fixate a point of intersection of the orthogonally oriented stimuli' because they reasoned that the 'relax and let your eyes choose a target' instruction may bias subjects towards one of the two targets and away from intermediate positions of focus. However, the 'fixate a point of intersection' instruction would also allow subjects to attend to either target.

Subject instructions are important because they influence the validity with which experimental results can be applied to real situations. Arguments could be made for the use of a passive instruction to simulate every-day situations. However, and this is important to note, for basic research it would be better to first investigate the response to conflicting targets using a definite instruction that requires attention to one of the conflicting targets. This would control for the variability that probably occurs when subjects are allowed to attend to either target. Later experiments could investigate situations in which people do not direct constant attention to one particular target.

Voluntary Accommodation. Mandelbaum concluded from his experiment that accommodation is a true reflex because subjects, even when they tried, could

not overcome the inappropriate accommodation response to an intervening window screen.[350] Owens, in his first experiment, measured accommodation in his subjects and found that a screen induces small shifts in accommodation that could not be overcome by conscious effort.[166] These results might suggest that voluntary accommodation is unable to overcome the Mandelbaum effect, but there is an alternative interpretation.

Owens noted subjects' perceptions of the conflicting target task (although he does not state whether these were *his* subjects' perceptions):

> Even after extensive practice, holding the near or far targets in focus required continuous effort. Any relaxation of this effort to focus the letter matrix and to ignore the screen usually resulted in an involuntary shift of accommodation to the screen if it was positioned at an intermediate distance.[166]

People probably use voluntary accommodation to overcome the Mandelbaum effect, but even with practice, a small residual shift in accommodation cannot be overcome by voluntary effort. Both Owens' and Mandelbaum's studies are consistent with (although they do not prove) this explanation of the role for voluntary accommodation in the Mandelbaum effect.

Further evidence suggests a role for voluntary accommodation in the Mandelbaum effect. One subject in Owens' first experiment (subject L.W.) improved with practice when viewing conflicting targets.[166] She may have improved her voluntary accommodation ability with practice at the task. Also, in Owen's second experiment, subjects tended to focus back and forward between targets when the two targets straddled their dark focus level. This may represent an instability of the reflex accommodation system, or it may be due to shifts of attention from one target to the other.[166]

Binocular versus Monocular viewing

Very little information is available that compares the Mandelbaum effect in binocular and monocular viewing. Mandelbaum noted that a window screen caused blurring of distant scenes at a shorter viewing distance for monocular

than for binocular viewing.[350] Collins *et al.* found that a grid reflection in the screen of a visual display terminal caused a significantly greater shift in accommodation away from the screen in monocular than in binocular viewing, but only in some viewing conditions.[355]

Target Position

If conflicting targets are beyond the far point or closer than the near point of accommodation then this will limit the magnitude of the Mandelbaum effect that can occur. However observations by Mandelbaum show that the Mandelbaum effect is not limited to young subjects with high amplitudes of accommodation. In a sub-group of subjects aged 40–57 years, Mandelbaum noted that a window screen caused maximal blurring of a distant sign when it was about 50 cm (2 D) from the eye.[350]

Target Separation in Relation to Depth of Focus

Adams and Johnson noted that at small target separations, subjects occasionally focused midway between two conflicting targets, probably because their depth of focus allowed both targets to remain clear.[353] Thus, in addition to the other effects it has on accommodation (section 1.5.6),[15] depth of focus may also influence the response to conflicting targets by increasing or decreasing the range of target separations over which both targets can be seen clearly when adopting an intermediate position of focus.

Past History of Response

I hypothesise that the prior adapting level of accommodation has an influence on the subsequent response to conflicting targets. That is, the accommodation response is dependent on its past history. This could be due to a number of factors.

Upper Blur Threshold. The *upper blur threshold of accommodation* is the maximum amount of target blur that can elicit an accommodation response. If the blur is greater than this threshold then no accommodation response occurs (see section 1.4.3.1). I hypothesise that if there are two conflicting targets and one is beyond the upper blur threshold, then accommodation does not respond to that target. The blur threshold will probably depend on

the spatial frequency content of a target, the presence or absence of proximal stimuli, and whether the subject is able to use voluntary accommodation (see section 1.4.3.1).

Adapting Level Effects. It may be that even if the various conflicting targets are within the upper blur threshold, a response away from a relatively clear target towards a more blurred target is difficult. For example, a pilot attempting to focus for a distant runway after viewing the cockpit instrument panel may find the task difficult because detail on the windshield is 'capturing' his/her focus. Most models of accommodation assume that the input to the neural controller in the brain is proportional to the amount of blur; that is, the higher the blur the greater the stimulus to accommodation. However it is possible that for fine focus control the accommodation controller uses the contrast gradient of the target image, and this contrast gradient falls off quickly with defocus.[226] Taking an alternative approach, accommodation probably responds best to mid spatial frequencies of a target ($\approx$ 4 cycles.degree^{-1}).[24,103] It may be that the primarily low spatial frequency information in a defocused target cannot compete against the higher contrast mid spatial frequencies in an already focused target. Note that this effect would occur even though the second target is within the upper blur threshold; that is, even though the second target *by itself* would elicit an accommodation response. This speculated effect, which I have called an *adapting level effect*, represents another situation where the accommodation response depends on its past history.

Tonic Adaptation Effects. Long term adaptation to a particular accommodation level may affect the accommodation response to conflicting targets because of tonic adaptation (see section 1.2.4.6). With time at a near task there is an inward shift in the resting point of accommodation, and under open-loop conditions the decay of accommodation towards the 'true' resting level is prolonged by pre-adaptation to a near task.[139,344] The research of Owens suggests that accommodation to conflicting targets is biased towards the target closest to the individual resting point of accommodation.[166] So, for

example, if a subject adapted for a long period at a near task before being presented with conflicting targets, then the inward shift in their resting level may bias the subject towards the nearer of two conflicting targets. These speculated effects I have called *tonic adaptation effects.*

Target Characteristics

The effect of target characteristics on the Mandelbaum effect has received little attention. Benel demonstrated that low contrast screen targets did not induce a Mandelbaum effect, while high contrast screens induced a shift of accommodation away from an attended Snellen letter matrix.[352]

Benel proposed using the slope of the accommodation stimulus–response function as an measure of a particular target's adequacy to induce a Mandelbaum effect.[352] The stimulus–response slope would take into account factors such as the luminance, contrast and spatial frequency content of a target, and would be simple to measure. The stimulus–response slopes for Benel's screen targets decreased as screen contrast was reduced, and the Mandelbaum effect also decreased as screen contrast was reduced.[352] This finding supports Benel's use of the stimulus–response slope as a measure of stimulus adequacy.

Peripheral or Central Location of Conflicting Targets

Accommodation responses become less accurate with increasing retinal eccentricity of a target (see section 1.5.4). Thus there is a potential for bias against a target depending on its retinal location.

Several studies have investigated the accommodation response in situations where there are conflicting central and peripheral target details. Some studies have provided both blur and proximal stimuli to accommodation,[288,290] while others have used Badal systems to reduce proximal stimuli.[250,289] When viewing a distant target through an aperture in a wall, accommodation tends to adopt a position intermediate between the two conflicting targets,[288,290] and becomes more accurate as the aperture size is increased.[290] These effects are not simply due to conflicting stimuli to

perceived distance because they are also present when viewing in Badal systems.[250,289]

Peripheral objects can cause a Mandelbaum effect, but their influence decreases with eccentricity. Other factors which may influence the adequacy of the peripheral target are the extent to which it obscures a distant target, and the amount of spatial detail in the peripheral target.[250]

Proximal Stimuli to Accommodation

Many studies of the Mandelbaum effect have presented targets optically in Badal systems. However in real life, conflicting targets also provide proximal stimuli to the accommodation system. No studies have specifically tried to determine the importance of proximal stimuli to the Mandelbaum effect, but there is a clue to suggest it may be important.

In his study, Mandelbaum noted that head movements could be used to overcome the unwanted accommodation response to a window screen.[350] Head movements may have aided Mandelbaum by blurring the contrast gradient of the screen detail relative to the stable distant target (see section 1.5.2.2). However, another interpretation is that the screen disrupts distance perception, leading to a perceptual flattening of the scene.[356,357] The parallax cue provided by head movements allows precise determination of the distance of the window screen, on par with normal stereoacuity.[242,358] With these distance cues it may then be possible to focus more correctly for the desired object.

1.8.1.5. APPLICATIONS OF THE MANDELBAUM EFFECT

Reduction in Acuity Caused by Defocus

Several researchers have investigated the reductions in acuity caused by inappropriate accommodation responses in the Mandelbaum effect.[159,290,350,359] Common situations in which this can occur are when driving a car, piloting an aircraft, or using a visual display terminal.[360] A mid-air collision between two aircraft over Zagreb, Yugoslavia in 1976 in

which the Mandelbaum effect may have played a part was researched by Roscoe and Hull.[359]

Accommodation Micropsia and Changes in Size and Distance Perception

Changes in accommodation can lead to changes in the perceived sizes of objects.[352,361,362] Increased accommodation leads to accommodation micropsia, and decreased accommodation leads to accommodation macropsia. These changes in perceived size are likely to have a central origin because they are still present in cyclopleged eyes attempting a change in accommodation.[361] Retinal stretch and changes in retinal image size with increased accommodation are too small to account for the reported changes in perceived size.[363,364] It has been hypothesised that these changes in perceived size may also lead to changes in perceived distance.[352,365]

Benel demonstrated that a conflicting target, by inducing a Mandelbaum effect, can alter the perceived size of a distant object.[352] Benel speculated on some potential applications of the Mandelbaum effect and accommodation micropsia. A driver following another vehicle on a road may wait too late to brake or to overtake if the rear of the car in front appeared smaller and more distant than usual due to accommodation micropsia. Due to a Mandelbaum effect, a pilot approaching a runway may perceive it to be smaller and more distant, and would probably 'carry more power to the runway, round out high, and land long and hard.'[352]

Asthenopia

The National Research Council (USA) considered it possible that inappropriate accommodation responses to screen reflections in visual display terminals may lead to user discomfort.[360] However the Mandelbaum effect induced by screen reflections in visual display terminals is small,[355] and would be unlikely to cause asthenopia.

Accommodation as a Mechanism to Perceptually Separate Superimposed Images

When presented with a real life scene composed of various overlapping objects, the visual system must have some way of separating the various objects. If a person's field of view is filled with objects at different distances

then, depending on the person's accommodation level, some of the objects may be clear while others are blurred. A clear object and a blurred object are obviously at different distances, and this could act as a cue to perceptually separate the objects. This cue may be useful for close objects, but would not operate for distant objects.[366] This is because objects in the distance must be separated by large physical distances before an observer can tell that one is more blurred than the other.

1.8.2. Effects of Astigmatism on Accommodation

1.8.2.1. SITUATIONS IN WHICH ASTIGMATISM IS PRESENT

Natural ocular astigmatism is widely prevalent but has an insignificant magnitude in a large proportion of the population.[367,368] The eye also exhibits peripheral astigmatism.[296,369] Astigmatism may be induced when either the cylindrical power or axis of a spectacle correction is incorrect. If a spectacle lens is tilted to the visual axis, astigmatism also occurs. Off-axis viewing through the spectacle lens also induces oblique astigmatism.[370] Finally, astigmatism can be induced when viewing off-axis through optical systems such as telescopes.[371]

1.8.2.2. CONFLICTING STIMULI PROVIDED BY ASTIGMATISM

In the presence of astigmatism an astigmatic focal interval is formed within the eye consisting of anterior and posterior focal lines and a circle of least confusion at the dioptric centre of the focal interval.[304,372] The presence of astigmatism provides conflicting stimuli to accommodation because in many cases accommodation may be used to bring any of various portions of the focal interval conjugate with the retina. In some cases the focal interval is only partially accessible or not accessible at all.

Several factors based on simple optics determine how much of the astigmatic focal interval is accessible to accommodation and these are: the form of astigmatism; the magnitude of astigmatism; the degree of spherical refractive error; the optical correction in place (if any); the distance to the object of regard; and the far and near points of accommodation.

1.8.2.3. FOCUS STRATEGIES WITH ASTIGMATISM

There are many possibilities for the focus position adopted in the presence of astigmatism:

1. The circle of least confusion;[372,373]
2. The anterior focal line;
3. The posterior focal line;[374]
4. Other intermediate positions in the focal interval;
5. Positions outside the focal interval;
6. The vertical focal line;[375]
7. The focal line closest to the dark focus of accommodation;
8. The focal line just posterior to the retina;[376]
9. Accommodation could oscillate to bring both line focii into focus successively.[38,212]

A number of experimental studies have shown that some subjects preferentially focus for positions that would provide good acuity such as the circle of least confusion,[38,377] and focal lines corresponding to target detail where the detail is parallel or perpendicular to the axis of astigmatism.[371,377] Some subjects prefer vertical detail while others prefer horizontal detail.[371]

Some subjects focus for the focal line that requires the least accommodation effort.[262,376] Infants possibly focus within the astigmatic interval, and they may not need to preferentially focus different portions of the astigmatic interval due to their greater depth of focus.[378,379] One study using a subjective optometer and others using cinematographic techniques noted fluctuations of accommodation across the astigmatic interval, possibly due to the subjects hunting for a focus position.[38,39,371] Some subjects do not show a preference for a particular focus position.[377]

1.8.2.4. FACTORS IN THE ACCOMMODATION RESPONSE WITH ASTIGMATISM

Target Detail & Visual Task

When target detail is oblique to the axis of astigmatism, people tend to make dynamic changes in their accommodation, hunting for a better focus position.[371] It may be that the task affects the preferred focus position. If

subjects are trying to discern a target's detail they may adopt different focus positions than when they simply look at the target.

Depth of Focus

If the depth of focus is large compared with the astigmatic interval then preferential accommodation would not be required. This may explain the lack of preferential focusing for target detail in infants.[379]

Natural versus Induced Astigmatism

Some natural astigmats have a meridional amblyopia[380] and may preferentially focus target detail parallel to their meridian of best acuity,[376] although this has not been definitely established. The oblique effect* in normal subjects does not affect accommodation accuracy.[381]

Further research is needed to determine the dynamic characteristics of accommodation in both natural astigmats and during induced astigmatism. The relationship between the fluctuations of accommodation and visual acuity needs to be investigated, as it may be that people can obtain better acuity when astigmatism is present if they make dynamic fluctuations in focus and integrate visual information over time.

1.8.3. Accommodation to Coloured Targets

The eye has about 2 D of longitudinal chromatic aberration between the wavelengths of 400–700 nm.[116,227,382,383] When viewing a non-monochromatic target this chromatic aberration leads to coloured fringes around the edges of the retinal image of the target.[176] Also, the different wavelengths are brought to a focus at different dioptric distances, and thus provide potentially conflicting stimuli to accommodation.

1.8.3.1. EFFECTS OF TARGET COLOUR ON ACCOMMODATION

There are three main issues in the accommodation response to coloured targets: chromatic aberration as a cue to accommodation; poor

* The oblique effect is the reduction in acuity for target detail oriented along oblique meridians in comparison to the vertical and horizontal meridians. It is observed even when astigmatic refractive errors are fully corrected.

accommodation responses to isoluminant colour contours; and conflicting stimuli to accommodation induced by chromatic aberration of the eye.

Chromatic Aberration as a Cue to Accommodation

Many people use the coloured fringes in the retinal image as a cue to accommodation.[176,177] Thus, these people have poorer accommodation responses when viewing dynamic targets of limited spectral bandwidth.[237,238] In accommodation to steady targets these effects are not noticed, possibly because people can use voluntary accommodation to obtain a better focus with time.[149,231] These factors are discussed in more detail in a previous section (section 1.4.1.2).

Accommodation Responses to Isoluminant Colour Contours

Accommodation is poor to isoluminant colour contours,[232,233] possibly due to a disruption in the normal arrangement of colour fringes in the retinal image of a target.[176]

1.8.3.2. CONFLICTING COLOUR STIMULI TO ACCOMMODATION

Static Targets

When viewing targets with a wide spectral distribution the wavelength apparently focused by the eye shifts towards lower wavelengths in near vision,[384,385] leading Ivanoff to conclude that the eye preferentially focuses the lower wavelengths to spare accommodation effort. However if accommodation responses in white and monochromatic light are compared then it is found that the responses are fairly similar in both situations.[149,386] Thus the so called sparing of accommodation in white light probably only represents the normal lead–lag characteristics of steady state accommodation (section 1.2.1).

Accommodation responses to single target colours tend to correct for the eye's chromatic aberration, that is, responses are higher for red than for blue targets.[149,387] Subjects differ in their responses to multicoloured targets. For example, Charman found the following response patterns when subjects viewed red on blue or blue on red targets: consistent focus for the red

wavelengths, consistent focus for the blue wavelengths, consistent focus for the background colour, consistent focus for the letter colour, focusing for either the red or blue wavelengths, or a response independent of colour. Obviously, group mean data in this situations would not be representative.[387]

The requirement for differential accommodation to targets of different colours can be reduced if more desaturated colours with wider spectral composition are used.[388,389]

Dynamic Stimuli

Subjects can make appropriate responses to alternating red and blue targets, but these responses need to be learned and are not reflex in nature.[149] Also, the responses depend on whether the subject tries to keep one or other of the target colours in focus.

More research is needed on the dynamics of accommodation when viewing colour targets. For example, when viewing static multi-colour displays it may be that the fluctuations of accommodation increase due to alternate focusing between target detail of different colours.

1.8.4. Anisometropic Stimuli to the Two Eyes

During binocular viewing the accommodation responses in the two eyes are fairly tightly coupled in humans, although several studies have shown that anisometropic stimuli to accommodation can lead to different accommodation responses in the two eyes.

1.8.4.1. SYMMETRIC CONVERGENCE AND ANISOMETROPIC BLUR STIMULI

During symmetric convergence for a target, some studies have shown small differences in accommodation between the two eyes if lenses are placed in front of one eye to provide anisometropic stimuli to accommodation. Typical differences of accommodation between the two eyes can range up to 0.9 D for lens powers up to 1 D.[390,391] Some of the differences are too small to reach significance. Flitcroft *et al.* provided both humans and monkeys with

dynamic anisometropic stimuli and found that the responses tended to be an average of the two stimuli to the two eyes.[392] Kotulak and Morse measured accommodation responses of subjects while they viewed through a binocular instrument on which the eyepieces had been adjusted to provide different stimuli to the two eyes.[393] In contrast to Flitcroft *et al.* they found the accommodation response tended to follow the stimulus from one eye or the other, but not an average of the stimuli to the two eyes. Subjects had a tendency to focus for the target closest to their dark focus level, similar to results reported by other studies for conflicting targets in monocular viewing.[166,353]

1.8.4.2. ACCOMMODATION DURING ASYMMETRIC CONVERGENCE

During asymmetric convergence the object of regard is closer to one eye than the other, and this difference depends on the angle of asymmetric convergence and the distance of the target from the eyes. In some situations differences of accommodation between the two eyes of up to 2 D have been reported in asymmetric convergence,[394] although the differences are usually smaller than this.[391,395]

Unpublished Manuscript

a. Collins, M., B. Davis and J. Wood. Microfluctuations of steady-state accommodation and the cardiopulmonary system.

References

1. Fincham, E.F. The mechanism of accommodation. *Br. J. Ophthalmol.* 1937, (Monograph Supplement 8), 7–80.
2. Ali, M.A. and M.A. Klyne. *Vision in Vertebrates*. New York: Plenum Press, 1985. pp. 73–92.
3. Walls, G.L. *The Vertebrate Eye and its Adaptive Radiation*. New York: Hafner Publishing, 1963. pp. 247–288.
4. Duke-Elder, W.S., Sir and D. Abrams. *System of Ophthalmology*. London: Henry Kimpton, 1970. vol. 5, Ophthalmic optics and refraction. p. 153.
5. Barrow, C.A. *Beiträge zur Physiologie und Physik des menschlichen Auges*. Berlin: 1841. p. 212. Cited in: Duke–Elder & Abrams (1970). See reference 4.
6. Cline, D., H.W. Hofstetter and J.R. Griffin. *Dictionary of Visual Science*. 3rd ed. Pennsylvania: Chilton Book Company, 1980.

7. Heath, G.G. Components of accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**(11), 569–579.
8. Morgan, M.W. Accommodation and its relationship to convergence. *Am. J. Optom. Arch. Am. Acad. Optom.* 1944, **21**, 183–195.
9. Heath, G.G. The influence of visual acuity on accommodative responses of the eye. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**(10), 513–524.
10. Hamasaki, D., J. Ong and E. Marg. The amplitude of accommodation in presbyopia. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**(1), 3–14.
11. Alpern, M. and H. David. Effects of illuminance quantity on accommodation of the eyes. *Ind. Med. Surg.* 1958, **27**, 551–555.
12. Charman, W.N. and J. Tucker. Dependence of accommodation response on the spatial frequency spectrum of the observed object. *Vision Res.* 1977, **17**, 129–139.
13. Charman, W.N. and J. Tucker. Accommodation as a function of object form. *Am. J. Optom. Physiol. Opt.* 1978, **55**(2), 84–92.
14. Ukai, K. and S. Ishikawa. A quasistatic study on accommodation [in Japanese]. *Nippon Ganka Gakkai Zasshi.* 1983, **87**(12), 1428–1434.
15. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction.* Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
16. Nadell, M.C. and H.A. Knoll. The effect of luminance, target configuration and lenses upon the refractive state of the eye. Part 1. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**, 24–42.
17. Ward, P.A. and W.N. Charman. Effect of pupil size on steady state accommodation. *Vision Res.* 1985, **25**(9), 1317–1326.
18. Miege, C. and P. Denieul. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 165–171.
19. Bannon, R.E. The use of cycloplegics in refraction. *Am. J. Optom. Arch. Am. Acad. Optom.* 1947, **24**(11), 513–568.
20. Hung, G.K. and J.L. Semmlow. Static behavior of accommodation and vergence: computer simulation of an interactive dual–feedback system. *IEEE Trans. Bio.-Med. Eng.* 1980, **BME-27**(8), 439–447.
21. McBrien, N.A. and M. Millodot. The effect of refractive error on the accommodative response gradient. *Ophthalmic Physiol. Opt.* 1986, **6**(2), 145–149.
22. Ciuffreda, K.J., S.C. Hokoda, G.K. Hung and J.L. Semmlow. Accommodative stimulus/response function in human amblyopia. *Doc. Ophthalmol.* 1984, **56**(4), 303–326.
23. Tan, R.K.T. and D.J. O'Leary. Accommodation characteristics before and after near work. *Clin. Exp. Optom.* 1988, **71**, 165–169.
24. Owens, D.A. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980, **20**, 159–167.
25. Denieul, P. Effects of stimulus vergence on mean accommodation response, microfluctuations of accommodation and optical quality of the human eye. *Vision Res.* 1982, **22**(5), 561–569.
26. Toates, F.M. Accommodation function of the human eye. *Physiol. Rev.* 1972, **52**(4), 828–863.
27. Kasai, T., K. Kondo, M. Sekiguchi and K. Fujii. Influence of the depth of focus on the human eye accommodation. *Japanese Journal of Medical Electronics and Biological Engineering.* 1971, **9**(1), 28–36.

28. Krishnan, V.V. and L.W. Stark. Integral control in accommodation. *Comput. Programs Biomed.* 1975, **4**, 237–245.
29. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.
30. Charman, W.N. Static accommodation and the minimum angle of resolution. *Am. J. Optom. Physiol. Opt.* 1986, **63**(11), 915–921.
31. Collins, G. The electronic refractionometer. *Br. J. Physiol. Opt.* 1937, **11**(1), 30–42.
32. Fincham, E.F. The accommodation reflex and its stimulus. *Br. J. Ophthalmol.* 1951, **35**, 381–393.
33. Arnulf, A., O. Dupuy and F. Flamant. Les microfluctuations d'accommodation de l'oeil et l'acuite visuelle pour les diametres pupillaires naturels. *Comptes Rendus Hebdomadaires des Seances. Academie des Sciences (Paris).* 1951, **232**, 349–350.
34. Arnulf, A., O. Dupuy and F. Flamant. Les microfluctuations de l'œil et leur influence sur l'image rétinienne. *Comptes Rendus Hebdomadaires des Seances. Academie des Sciences (Paris).* 1951, **232**, 438–440.
35. Arnulf, A., O. Dupuy and F. Flamant. Les microfluctuations d'accommodation de l'oeil. *Ann. Opt. Oculaire.* 1955, **3**(5), 109–118.
36. Arnulf, A. and O. Dupuy. Contribution a l'etude des microfluctuations d'accommodation de l'œil. *Revue d'Optique.* 1960, **39**, 195–208.
37. Arnulf, A., J. Santamaria and J. Bescos. Cinematographic recording of retinal images. New contributions to the study of microfluctuations of the accommodation. *In: ICO-11 Conference.* International Commission for Optics, 1978. pp. 47–50.
38. Arnulf, A., J. Santamaria and J. Bescos. A cinematographic method for the dynamic study of the image formation by the human eye. Microfluctuations of the accommodation. *J. Opt. (Paris).* 1981, **12**(2), 123–128.
39. Santamaria, J., A. Plaza and J. Bescos. Dynamic recording of the binocular point spread function of the eye optical system. *Opt. Appl.* 1984, **14**(3), 341–347.
40. Alpern, M. Variability of accommodation during steady fixation at various levels of illuminance. *J. Opt. Soc. Am.* 1958, **48**(3), 193–197.
41. Westheimer, G. Accommodation measurements in empty visual fields. *J. Opt. Soc. Am.* 1957, **47**(8), 714–718.
42. Allen, M.J. The stimulus to accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1955, **32**, 422–431.
43. Campbell, F.W., J.G. Robson and G. Westheimer. The control of accommodation in the human eye. *In: Proceedings of the 2nd International Congress on Cybernetics.* 1958. pp. 924–929.
44. Campbell, F.W., G. Westheimer and J.G. Robson. Significance of fluctuations of accommodation. *J. Opt. Soc. Am.* 1958, **48**, 669.
45. Campbell, F.W., J.G. Robson and G. Westheimer. Fluctuations of accommodation under steady viewing conditions. *J. Physiol.* 1959, **145**, 579–594.
46. Campbell, F.W. Correlation of accommodation between the two eyes. *J. Opt. Soc. Am.* 1960, **50**(7), 738.
47. Campbell, F.W. and J.G. Robson. High-speed infra-red optometer. *J. Opt. Soc. Am.* 1959, **49**(3), 268–272.
48. Stark, L.W., Y. Takahashi and G. Zames. Nonlinear servoanalysis of human lens accommodation. *IEEE Trans. Syst. Sci. Cybern.* 1965, **SSC-1**(1), 75–83.

49. Krueger, H. Schwankungen der Akkommodation des menschlichen Auges bei mon- und binokularer Beobachtung. *Albrecht von Graefes Arch. klin. exp. Ophthalmol. (Berl.)*. 1978, **205**, 129–133.
50. Bour, L.J. The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Res.* 1981, **21**, 1287–1296.
51. Kotulak, J.C. and C.M. Schor. Temporal variation in accommodation during steady-state conditions. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1986, **3**(2), 223–227.
52. Winn, B., J.R. Pugh, B. Gilmartin and H. Owens. Arterial pulse modulates steady-state ocular accommodation. *Curr. Eye Res.* 1990, **9**(10), 971–975.
53. Winn, B., W.N. Charman, J.R. Pugh, G. Heron and A.S. Eadie. Perceptual detectability of ocular accommodation microfluctuations. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1989, **6**(3), 459–462.
54. Owens, H., B. Winn, B. Gilmartin and J.R. Pugh. Effect of a topical beta-adrenergic receptor antagonist on the dynamics of steady-state accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**(4), 99–104.
55. Winn, B., J.R. Pugh, B. Gilmartin and H. Owens. The frequency characteristics of accommodative microfluctuations for central and peripheral zones of the human crystalline lens. *Vision Res.* 1990, **30**(7), 1093–1099.
56. Charman, W.N. and G. Heron. Fluctuations in accommodation: a review. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 153–164.
57. Heron, G. *A Study of Accommodation using an Infra-red Optometer*. MSc Thesis. Manchester, UK: University of Manchester, 1972. Cited in: Charman & Heron (1988). See reference 56.
58. Eadie, A.S. The synchronicity of microfluctuations in accommodation and miniature eye movements [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1307.
59. Campbell, F.W. and G. Westheimer. Sensitivity of the eye to differences in focus [Abstract]. *Journal of Physiology. Supplementum.* 1958, **143**, 18P.
60. Walsh, G. and W.N. Charman. Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Res.* 1988, **28**(11), 1207–1221.
61. Millodot, M. Effet des microfluctuations de l'accommodation sur l'acuite visuelle. *Vision Res.* 1968, **8**, 73–80.
62. Stark, L.W. *Neurological Control Systems. Studies in Bioengineering*. New York: Plenum Press, 1968. p. 217.
63. Hung, G.K., J.L. Semmlow and K.J. Ciuffreda. Accommodative oscillation can enhance average accommodative response: a simulation study. *IEEE Trans. Syst., Man, Cybern.* 1982, **SMC-12**(4), 594–598.
64. Sun, F., S. Brandt, A. Nguyen, M. Wong and L.W. Stark. Frequency analysis of accommodation: single sinusoids. *Ophthalmic Physiol. Opt.* 1989, **9**(4), 392–397.
65. Gray, L.S., B. Winn and B. Gilmartin. Accommodative microfluctuations and pupil diameter. *Vision Res.* 1993, **33**(15), 2083–2090.
66. Gray, L.S., B. Winn and B. Gilmartin. Effect of target luminance on microfluctuations of accommodation. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 258–265.
67. Pugh, J.R., A.S. Eadie , B. Winn and G. Heron. Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic Physiol. Opt.* 1987, **7**(3), 321–324.
68. Campbell, F.W. Accommodation reflex. *Br. Orthopt. J.* 1954, **11**, 13–17.
69. Fender, D.H. Control mechanisms of the eye. *Sci. Am.* 1964, **211**(1), 24–33.

70. Crane, H.D. *A theoretical analysis of the visual accommodative system in humans.* Menlo Park, California: Stanford Research Institute, 1966. (NASA Contractor Report NASA CR-606.)
71. Phillips, S. and L.W. Stark. Blur: a sufficient accommodative stimulus. *Doc. Ophthalmol.* 1977, **43**(1), 65–89.
72. Kotulak, J.C. and C.M. Schor. A computational model of the error detector of human visual accommodation. *Biol. Cybern.* 1986, **54**, 189–194.
73. Walsh, G. and W.N. Charman. The subjective sensitivity to small changes in the contrast of a suprathreshold grating. *Vision Res.* 1990, **30**(1), 163–173.
74. Owens, H., K. Bhat and R.J. Jacobs. Maxwellian and real pupils: effects on accommodative microfluctuations [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1280.
75. Ward, P.A. The effect of spatial frequency on steady-state accommodation. *Ophthalmic Physiol. Opt.* 1987, **7**(3), 211–217.
76. Ujike, H. and M. Ikeda. Dependence of micro-accommodation responses on contrast and spatial frequency of the square-wave grating [in Japanese]. *Jap. J. Opt.* 1990, **7**, 454–460.
77. Denieul, P., H. Brettel and F. Martin-Corno. Accommodative responses to simple sinusoidal and compound gratings: role of spatial phase [Abstract]. *Optom. Vision Sci., Suppl.* 1992, **69**(12s), 144.
78. Whiteside, T.C.D. *The Problems of Vision in Flight at High Altitude.* London: Butterworths, 1957. pp. 85–92.
79. Heron, G., B. Winn, J.R. Pugh and A.S. Eadie. Twin channel infrared optometer for recording binocular accommodation. *Optom. Vision Sci.* 1989, **66**(2), 123–129.
80. Strang, N.C., B. Winn and B. Gilmartin. The influence of sympathetic innervation of ciliary smooth muscle on closed-loop accommodation [Abstract]. *Optom. Vision Sci., Suppl.* 1993, **70**(12s), 57.
81. Gray, L.S., B. Winn and B. Gilmartin. Simultaneous recording of continuous accommodation and pupil responses during sustained viewing of VDTs [Abstract]. *Optom. Vision Sci., Suppl.* 1993, **70**(12s), 150.
82. Allen, M.J. An investigation of the time characteristics of accommodation and convergence of the eyes. Historical review. *Am. J. Optom. Arch. Am. Acad. Optom.* 1953, **30**(2), 78–83.
83. Ferree, C.E. and G. Rand. The speed of adjustment of the eye for clear seeing at different distances. A study of ocular functions with special reference to aviation. *Am. J. Psychol.* 1919, **30**, 40–61.
84. Tefft, L.E. and E.K. Stark. Speed of accommodation as a practicable test for fliers. *Am. J. Ophthalmol.* 1922, **5**, 339–342.
85. Allen, M.J. An investigation of the time characteristics of accommodation and convergence of the eyes. Subjective determination of accommodation and objective recording of convergence. *Am. J. Optom. Arch. Am. Acad. Optom.* 1953, **30**(8), 393–402.
86. Campbell, F.W. and G. Westheimer. Dynamics of accommodation responses of the human eye. *J. Physiol.* 1960, **151**, 285–295.
87. Carter, J.H. A servoanalysis of the human accommodative mechanism. *Arch. Soc. Am. Oftalmol. Optom.* 1962, **4**, 137–168.
88. O'Neill, W.D. and L.W. Stark. Triple-function ocular monitor. *J. Opt. Soc. Am.* 1968, **58**(4), 570–573.
89. Phillips, S., D. Shirachi and L.W. Stark. Analysis of accommodative response times using histogram information. *Am. J. Optom. Arch. Am. Acad. Optom.* 1972, **49**(5), 389–401.

90. Shirachi, D., J. Liu, M. Lee, J. Jang, J. Wong and L.W. Stark. Accommodation dynamics. 1. Range nonlinearity. *Am. J. Optom. Physiol. Opt.* 1978, **55**(9), 631–641.
91. Tucker, J. and W.N. Charman. Reaction and response times for accommodation. *Am. J. Optom. Physiol. Opt.* 1979, **56**(8), 490–503.
92. Heron, G. and B. Winn. Binocular accommodation reaction and response times for normal observers. *Ophthalmic Physiol. Opt.* 1989, **9**(2), 176–183.
93. Randle, R.J. and M.R. Murphy. The dynamic response of visual accommodation over a seven-day period. *Am. J. Optom. Physiol. Opt.* 1974, **51**, 530–544.
94. Thompson, H.E. *The Dynamics of Accommodation in Primates.* PhD Thesis. Chicago: University of Illinois, 1975.
95. Myers, G.A. and L.W. Stark. Topology of the near response triad. *Ophthalmic Physiol. Opt.* 1990, **10**(2), 175–181.
96. Charman, W.N. and G. Heron. Spatial frequency and the dynamics of the accommodation response. *Opt. Acta (Lond.).* 1979, **26**(2), 217–228.
97. Kirchhof, H. A method for the objective measurement of accommodation speed of the human eye. The accommodation speed and its modification due to fatigue, eserine, pilocarpine and homatropine. translated by H.A. Knoll, M.J. Allen. *Am. J. Optom. Arch. Am. Acad. Optom.* 1950, **27**(4), 163–178.
98. Kasai, T., M. Unno, K. Fujii, M. Sekiguchi and K. Shinohara. Dynamic characteristics of human eye accommodation system. *Osaka University Technical Reports.* 1971, **21**, 569–586.
99. Hung, G.K. and K.J. Ciuffreda. Dual-mode behaviour in the human accommodation system. *Ophthalmic Physiol. Opt.* 1988, **8**(3), 327–332.
100. Krishnan, V.V., S. Phillips and L.W. Stark. Frequency analysis of accommodation, accommodative vergence and disparity vergence. *Vision Res.* 1973, **13**, 1545–1554.
101. van der Wildt, G.J., M.A. Bouman and J. van de Kraats. The effect of anticipation on the transfer function of the human lens system. *Opt. Acta (Lond.).* 1974, **21**(11), 843–860.
102. Takagi, M., H. Abe, H. Toda and T. Usui. Accommodative and pupillary responses to sinusoidal target depth movement. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 253–257.
103. Mathews, S. and P.B. Kruger. Spatiotemporal transfer function of human accommodation. *Vision Res.* 1994, **34**, 1965–1980.
104. Sun, F. and L.W. Stark. Switching control of accommodation: experimental and simulation responses to ramp inputs. *IEEE Trans. Bio.-Med. Eng.* 1990, **37**(1), 73–79.
105. Rosenfield, M., K.J. Ciuffreda, G.K. Hung and B. Gilmartin. Tonic accommodation: a review. I. Basic aspects. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 266–284.
106. Leibowitz, H.W. and D.A. Owens. Anomalous myopias and the intermediate dark focus of accommodation. *Science.* 1975, **189**, 646–648.
107. Leibowitz, H.W., R.T. Hennessy and D.A. Owens. The intermediate resting position of accommodation and some implications for space perception. *Psychologia.* 1975, **18**, 162–170.
108. Helmholtz, H., von. *Helmholtz's Treatise on Physiological Optics* [Handbuch der Physiologischen Optik]. translated and edited by J.P.C. Southall. Menasha, Wisconson: Optical Society of America & George Banta Publishing, [1909–1911] 1924. vol. 1. p. 151.
109. Leibowitz, H.W. and D.A. Owens. New evidence for the intermediate position of relaxed accommodation. *Doc. Ophthalmol.* 1978, **46**(1), 133–147.
110. Ciuffreda, K.J. and D. Rumpf. Contrast and accommodation in amblyopia. *Vision Res.* 1985, **25**(10), 1445–1457.

111. Ward, P.A. The effect of stimulus contrast on the accommodation response. *Ophthalmic Physiol. Opt.* 1987, **7**(1), 9–16.
112. Ward, P.A. and W.N. Charman. On the use of small artificial pupils to open-loop the accommodation system. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 191–193.
113. Kotulak, J.C. and C.M. Schor. The effects of optical vergence, contrast, and luminance on the accommodative response to spatially bandpass filtered targets. *Vision Res.* 1987, **27**(10), 1797–1806.
114. Westheimer, G. and S.M. Blair. Accommodation of the eye during sleep and anesthesia. *Vision Res.* 1973, **13**, 1035–1040.
115. Koomen, M., R. Scolnik and R. Tousey. A study of night myopia. *J. Opt. Soc. Am.* 1951, **41**, 80–90.
116. Wald, G. and D.R. Griffin. The change in refractive power of the human eye in dim and bright light. *J. Opt. Soc. Am.* 1947, **37**(5), 321–336.
117. Gilmartin, B. A review of the role of sympathetic innervation of the ciliary muscle in ocular accommodation. *Ophthalmic Physiol. Opt.* 1986, **6**(1), 23–37.
118. Rosenfield, M. Comparison of accommodative adaptation using laser and infra-red optometers. *Ophthalmic Physiol. Opt.* 1989, **9**, 431–436.
119. Rosenfield, M. and K.J. Ciuffreda. Effect of surround propinquity on the open-loop accommodative response. *Invest. Ophthalmol. Visual Sci.* 1991, **32**, 1, 142–147.
120. Rosenfield, M., K.J. Ciuffreda and G.K. Hung. The linearity of proximally induced accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1991, **32**(11), 2985–2991.
121. Rosenfield, M. and K.J. Ciuffreda. Proximal and cognitively-induced accommodation. *Ophthalmic Physiol. Opt.* 1990, **10**, 252–256.
122. Winn, B., B. Gilmartin, L.C. Mortimer and N.R. Edwards. The effect of mental effort on open- and closed-loop accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**(4), 335–339.
123. Krumholz, D.M., R.S. Fox and K.J. Ciuffreda. Short-term changes in tonic accommodation. *Invest. Ophthalmol. Visual Sci.* 1986, **27**(4), 552–557.
124. Post, R.B., C.A. Johnson and T.K. Tsuetaki. Comparison of laser and infrared techniques for measurement of resting focus of accommodation: mean differences and long-term variability. *Ophthalmic Physiol. Opt.* 1984, **4**(4), 327–332.
125. Miller, R.J. Temporal stability of the dark focus of accommodation. *Am. J. Optom. Physiol. Opt.* 1978, **55**(7), 447–450.
126. Heron, G., A.C. Smith and B. Winn. The influence of method on the stability of dark focus position of accommodation. *Ophthalmic Physiol. Opt.* 1981, **1**(2), 79–90.
127. Owens, R.L. and K.E. Higgins. Long-term stability of the dark focus of accommodation. *Am. J. Optom. Physiol. Opt.* 1983, **60**(1), 32–38.
128. Jaschinski-Kruza, W. On proximal effects in objective and subjective testing of dark accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**, 328–334.
129. Phillips, S.R. *Ocular Neurological Control Systems: Accommodation and the Near Response Triad.* PhD Thesis. Berkeley: University of California, 1974. pp. 74–122; 123–156; 340–360.
130. Schor, C.M., J.C. Kotulak and T. Tsuetaki. Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. *Invest. Ophthalmol. Visual Sci.* 1986, **27**(5), 820–827.
131. Wolfe, J.M. and K.M. O'Connell. Adaptation of the resting states of accommodation. *Invest. Ophthalmol. Visual Sci.* 1987, **28**(6), 992–996.

132. Fisher, S.K., K.J. Ciuffreda and J.E. Bird. The effect of monocular versus binocular fixation on accommodative hysteresis. *Ophthalmic Physiol. Opt.* 1988, **8**(4), 438–442.
133. Rosenfield, M. and B. Gilmartin. Temporal aspects of accommodative adaptation. *Optom. Vision Sci.* 1989, **66**(4), 229–234.
134. Schor, C.M., C.A. Johnson and R.B. Post. Adaptation of tonic accommodation. *Ophthalmic Physiol. Opt.* 1984, **4**(2), 133–138.
135. Bullimore, M.A. and B. Gilmartin. The measurement of adaptation of tonic accommodation under two open-loop conditions. *Ophthalmic Physiol. Opt.* 1989, **9**(1), 72–75.
136. Malmstrom, F.V. and R.J. Randle. Effects of visual imagery on the accommodation response. *Percept. Psychophys.* 1976, **19**(5), 450–453.
137. Wolf, K.S., K.J. Ciuffreda and S.E. Jacobs. Time course and decay of effects of near work on tonic accommodation and tonic vergence. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 131–136.
138. Schor, C.M. and J.C. Kotulak. Dynamic interactions between accommodation and convergence are velocity sensitive. *Vision Res.* 1986, **26**(6), 927–942.
139. Schor, C.M. The Glen A. Fry Award Lecture: Adaptive regulation of accommodative vergence and vergence accommodation. *Am. J. Optom. Physiol. Opt.* 1986, **63**(8), 587–609.
140. Rosenfield, M. and B. Gilmartin. The effect of vergence adaptation on convergent accommodation. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 172–177.
141. Kotulak, J.C. and C.M. Schor. The accommodative response to subthreshold blur and perceptual fading during the Troxler phenomenon. *Perception.* 1986, **15**, 7–15.
142. Campbell, F.W. The accommodation response of the human eye. *Br. J. Physiol. Opt.* 1959, **169**(4), 188–203.
143. Marg, E. An investigation of voluntary as distinguished from reflex accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1951, **28**, 347–356.
144. Schor, C.M., J. Alexander, L. Cormack and S. Stevenson. Negative feedback control model of proximal convergence and accommodation. *Ophthalmic Physiol. Opt.* 1992, **12**, 307–318.
145. Banks, M.S. Infant refraction and accommodation. *Int. Ophthalmol. Clin.* 1980, **20**, 205–232.
146. McKenzie, B.E. and R.H. Day. Distance as a determinant of visual function in early infancy. *Science.* 1972, **178**, 1108–1110.
147. Francis, E.L., J. Bai-Chuan, D.A. Owens, R.A. Tyrrell and H.W. Leibowitz. "Effort to see" affects vergence and accommodation but not their interactions [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1989, **30**(3), 135.
148. Ciuffreda, K.J. and P.B. Kruger. Dynamics of human voluntary accommodation. *Am. J. Optom. Physiol. Opt.* 1988, **65**(5), 365–370.
149. Charman, W.N. and J. Tucker. Accommodation and color. *J. Opt. Soc. Am.* 1978, **68**(4), 459–471.
150. Ciuffreda, K.J. and S.C. Hokoda. Effect of instruction and higher level control on the accommodative response spatial frequency profile. *Ophthalmic Physiol. Opt.* 1985, **5**(2), 221–223.
151. Provine, R.R. and J.M. Enoch. On voluntary ocular accommodation. *Percept. Psychophys.* 1975, **17**(2), 209–212.
152. Trachtman, J.N., V. Giambalvo and J. Feldman. Biofeedback of accommodation to reduce functional myopia. *Biofeedback Self-Regul.* 1981, **6**(4), 547–564.
153. Arion, A.F. De l'interet des images de Purkinje dans l'etude de la doiptrique dynamique de l'oeil. *Arch. Ophtalmol. (Paris).* 1967, **27**(3), 221–250.

154. Malmstrom, F.V. and R.J. Randle. Visual imagery in the third dimension: voluntary control of accommodation. *In: Proceedings of Psychology in the Air Force Symposium*. USAF Academy, Colorado: Department of Life and Behavioral Sciences, 1974. pp. 189–192.
155. Randle, R.J. Responses of myopes to volitional control training of accommodation. *Ophthalmic Physiol. Opt.* 1988, **8**(3), 333–340.
156. Randle, R.J. Volitional control of visual accommodation. *In: Conference Proceeding No. 82 on Adaptation and Acclimatization in Aerospace Medicine*. AGARD, NATO, 1971.
157. Gnadt, J.W. The relationship of accommodation and vergence during voluntary near response in the dark in monkeys [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1992, **33**(4), 1100.
158. Fincham, E.F. Accommodation and convergence in the absence of retinal images. *Vision Res.* 1962, **1**, 425–440.
159. Roscoe, S.N. and D.H. Couchman. Improving visual performance through volitional focus control. *Hum. Factors*. 1987, **29**(3), 311–325.
160. Kruger, P.B. and J. Pola. Changing target size is a stimulus for accommodation. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1985, **2**(11), 1832–1835.
161. McLin, L.N., C.M. Schor and P.B. Kruger. Changing size (looming) as a stimulus to accommodation and vergence. *Vision Res.* 1988, **28**(8), 883–898.
162. Troelstra, A., B.L. Zuber, D. Miller and L.W. Stark. Accommodative tracking: A trial-and-error function. *Vision Res.* 1964, **4**, 585–594.
163. Carr, H. and J.B. Allen. A study of certain relations of accommodation and convergence to the judgement of the third dimension. *Psychol. Rev.* 1906, **13**, 258–275.
164. Sisson, E.D. A case of voluntary control of accommodation. *J. Gen. Psychol.* 1937, **17**, 170–174.
165. Sisson, E.D. Voluntary control of accommodation. *J. Gen. Psychol.* 1938, **18**, 195–198.
166. Owens, D.A. The Mandelbaum effect: Evidence for an accommodative bias toward intermediate viewing distances. *J. Opt. Soc. Am.* 1979, **69**(5), 646–652.
167. McLin, L.M. and C.M. Schor. Voluntary effort as a stimulus to accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1988, **29**(11), 1739–1746.
168. Cornsweet, T.N. and H.D. Crane. Training the visual accommodation system. *Vision Res.* 1973, **13**, 713–715.
169. Randle, R.J. Visual accommodation. Mediated control and performance. *In:* D.J. Oborne ed. *International Reviews of Ergonomics*. London: Taylor & Francis, 1988. vol. 2. pp. 207–232.
170. Trachtman, J.N. Biofeedback of accommodation to reduce myopia: a review. *Am. J. Optom. Physiol. Opt.* 1987, **64**(8), 639–643.
171. Gilmartin, B., L.S. Gray and B. Winn. The amelioration of myopia using biofeedback of accommodation: a review. *Ophthalmic Physiol. Opt.* 1991, **11**, 304–313.
172. Trachtman, J.N. Biofeedback of accommodation to reduce myopia: a seven-year follow-up [Abstract]. *Am. J. Optom. Physiol. Opt.* 1984, **61**, 93P–94P.
173. Carr, H. Voluntary control of the distance location of the visual field. *Psychol. Rev.* 1908, **15**(3), 139–149.
174. Miller, N.E. The learning of visceral and glandular responses. *Science*. 1969, **163**, 434–445.
175. Campbell, F.W. The minimum quantity of light required to elicit the accommodation reflex in man. *J. Physiol.* 1954, **123**, 357–366.
176. Kruger, P.B., S. Mathews, K.R. Aggarwala and N. Sanchez. Chromatic aberration and ocular focus: Fincham revisited. *Vision Res.* 1993, **33**(10), 1397–1411.

177. Kruger, P.B., S. Mathews, E.S. Kruger and K.R. Aggarwala. Accommodation responds to changing contrast of the red, green and blue components of the retinal image [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1281.
178. Bando, T., M. Takagi, H. Toda and T. Yoshizawa. Functional roles of the lateral suprasylvian cortex in ocular near response in the cat. *Neurosci. Res.* 1992, **15**(3), 162–178.
179. Jampel, R.S. Convergence, divergence, pupillary reactions and accommodation of the eyes from faradic stimulation of the macaque brain. *J. Comp. Neurol.* 1960, **115**, 371–400.
180. Manor, R.S., Y.D. Heilbronn, I. Sherf and I. Ben-Sira. Loss of accommodation produced by peristriate lesion in man? *J. Clin. Neuro–Ophthalmol.* 1988, **8**(1), 19–23.
181. Bando, T. and H. Toda. Responses of extrastriate lens accommodation-related units to movement in depth and size change of visual target in cats [Abstract]. *Jap. J. Physiol.* 1989, **39**, S 165.
182. Toyama, K. and T. Kozasa. Responses of Clare-Bishop neurones to three-dimensional movement of a light stimulus. *Vision Res.* 1982, **22**, 571–574.
183. Kawasaki, T., M. Kiyosawa, T. Fujino and T. Tokoro. Slow accommodation release with a cerebellar lesion. *Br. J. Ophthalmol.* 1993, **77**(10), 678.
184. Zhang, H.Y. and P.D.R. Gamlin. Sensorimotor characteristics of far response neurons in the cerebellum of the Rhesus monkey [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1282.
185. Hosoba, M., T. Bando and N. Tsukahara. The cerebellar control of accommodation of the eye in the cat. *Brain Res.* 1978, **153**, 495–505.
186. Hultborn, H., K. Mori and N. Tsukahara. Cerebellar influence on parasympathetic neurones innervating intra-ocular muscles. *Brain Res.* 1978, **159**, 269–278.
187. Bando, T., N. Yamamoto and N. Tsukahara. Cortical neurons related to lens accommodation in posterior lateral suprasylvian area in cats. *J. Neurophysiol.* 1984, **52**(5), 879–891.
188. Hultborn, H., K. Mori and N. Tsukahara. The neuronal pathway subserving the pupillary light reflex. *Brain Res.* 1978, **159**, 255–267.
189. Bando, T., K. Tsukuda, N. Yamamoto, J. Maeda and N. Tsukahara. Physiological identification of midbrain neurons related to lens accommodation in cats. *J. Neurophysiol.* 1984, **52**(5), 870–878.
190. Judge, S.J. and B.G. Cumming. Neurons in the monkey midbrain with activity related to vergence eye movement and accommodation. *J. Neurophysiol.* 1986, **55**(5), 915–930.
191. Hiraoka, M. and M. Shimamura. The midbrain reticular formation as an integration center for the 'near reflex' in the cat. *Neurosci. Res.* 1989, **7**, 1–12.
192. Warwick, R. The ocular parasympathetic nerve supply and its mesencephalic sources. *Journal of Anatomy*. 1954, **88**, 71–93.
193. Jampel, R.S. and J. Mindel. The nucleus for accommodation in the midbrain of the macaque. The effect of accommodation, pupillary constriction, and extraocular muscle contraction produced by stimulation of the oculomotor nucleus on the intraocular pressure. *Invest. Ophthalmol.* 1967, **6**(1), 40–50.
194. Ruskell, G.L. and T. Griffiths. Peripheral nerve pathway to the ciliary muscle. *Exp. Eye Res.* 1979, **28**, 277–284.
195. Ruskell, G.L. Accommodation and the nerve pathway to the ciliary muscle: a review. *Ophthalmic Physiol. Opt.* 1990, **10**, 239–241.
196. Westheimer, G. and S.M. Blair. The parasympathetic pathways to internal eye muscles. *Invest. Ophthalmol.* 1973, **12**(3), 193–197.

197. Genis-Galvez, J.M. Innervation of the ciliary muscle. *Anat. Rec.* 1957, **127**, 219–230.
198. Wax, M.B. and P.B. Molinoff. Distribution and properties of beta-adrenergic receptors in human iris/ciliary body [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1984, **25**, 305.
199. Otsuka, N., K. Tsuchiya, K. Ukai, T. Yoshitomi and S. Ishikawa. Adrenergic receptors affect accommodation by modulating cholinergic activity [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1281.
200. Hagaiwara, H. and S. Ishikawa. The action potential of the ciliary muscle. *Ophthalmologica.* 1962, **144**, 323–340.
201. Stark, L.W. Presbyopia in light of accommodation. *Am. J. Optom. Physiol. Opt.* 1988, **65**(5), 407–416.
202. Davanger, M. The suspensory apparatus of the lens. The surface of the ciliary body. A scanning electron microscopic study. *Acta Ophthalmol. (Copenh.).* 1975, **53**, 19–33.
203. Farnsworth, P.N. and P. Burke. Three-dimensional architecture of the suspensory apparatus of the lens of the Rhesus monkey. *Exp. Eye Res.* 1977, **25**, 563–576.
204. Rohen, J.W. Scanning electron microscopic studies of the zonular apparatus in human and monkey eyes. *Invest. Ophthalmol. Visual Sci.* 1979, **18**(2), 133–144.
205. Scheiner. *Oculus hoc est: fundamentum opticum, Oeniponti.* 1619. Cited in: Duke–Elder & Abrams (1970). See reference 4.
206. Young, T. The Bakerian Lecture. On the mechanism of the eye. *Philosophical Transactions of the Royal Society of London.* 1801, (Part 1), 23–88. inc. 7 plates.
207. Kepler. *Dioptrice. Propos 64.* 1611. Cited in: Helmholtz (1924). See reference 108.
208. Coleman, D.J., D. Wuchinich and B. Carlin. Accommodative changes in the axial dimension of the human eye. *In:* K.A. Gitter, A.H. Keeney, L.K. Sarin and D. Meyer eds. *Ophthalmic Ultrasound. Proceedings of the Fourth International Congress of Ultrasonography in Ophthalmology, Philadelphia, Pennsylvania.* Saint Louis: C.V. Mosby, 1969. pp. 134–141.
209. Descartes, R. *Treatise of Man* [L'Homme de René Descartes]. translated by T.S. Hall. Cambridge, Massachusetts: Harvard University Press, [1664] 1972.
210. Lagenbeck. *Klinsche Beiträge aus dem Gebiete der Chirurgie und Ophthalmologie.* Göttingen: 1849. Cited in: Helmholtz (1924). See reference 108.
211. Helmholtz, H., von. Ueber die Accommodation des Auges. *Arch. Ophthalmol. (Berl.).* 1855, **1**, 1–74. Cited in: Helmholtz (1924). See reference 108.
212. Donders, F.C. *On the Anomalies of Accommodation and Refraction of the Eye.* London: The New Sydenham Society, 1864. p.470.
213. Cramer, A. *Het accommodatievermogen der Oogen, physiologisch toegelicht.* Haarlem: De Erven Loosjes, 1853. Cited in: Helmholtz (1924). See reference 108.
214. Graefe, A., von. Fall von acquirirter Aniridie als Beitrag zur Akkommodationslehre. *Arch. Ophthalmol. (Berl.).* 1860, **7**, 150–161. Cited in: Fincham (1937). See reference 1.
215. Tscherning, M. Théorie des changements optiques de l'oeil pendant l'accommodation. *Archives de Physiologie.* 1895, **7**. Cited in: Fincham (1937). See reference 1.
216. Tscherning, M.H.E. *Hermann v. Helmholtz et la theorie de l'accommodation.* Paris: O.Doin, 1909. Cited in: Fincham (1937). See reference 1.
217. Hill, L. *The Lancet.* 1920, (February 14). Cited in: Fincham (1937). See reference 1.
218. Gullstrand, A., von. The mechanism of accommodation. *In:* J.P.C. Southall ed. *Helmholtz's Treatise on Physiological Optics.* Menasha, Wisconson: Optical Society of America & George Banta Publishing, 1924. vol. 1. pp. 382–415.

219. Fincham, E.F. The change in the form of the crystalline lens in accommodation. *Trans. Opt. Soc. (Lond.)*. 1924-1925, **26**(5), 239–269.
220. Koretz, J.F. and G.H. Handelman. A model for accommodation in the young human eye: the effects of lens elastic anisotropy on the mechanism. *Vision Res.* 1983, **23**(12), 1679–1686.
221. Coleman, D.J. Unified model for accommodative mechanism. *Am. J. Ophthalmol.* 1970, **69**(6), 1063–1079.
222. Schachar, R.A. Cause and treatment of presbyopia with a method for increasing the amplitude of accommodation. *Ann. Ophthalmol.* 1992, **24**(12), 445–447, 452.
223. Schachar, R.A., D.P. Cudmore and T.D. Black. Experimental support for Schachar's hypothesis of accommodation. *Ann. Ophthalmol.* 1993, **25**(11), 404–409.
224. Schachar, R.A., T. Huang and X. Huang. Mathematical proof of Schachar's hypothesis of accommodation. *Ann. Ophthalmol.* 1993, **25**(1), 5–9.
225. Smithline, L.M. Accommodative response to blur. *J. Opt. Soc. Am.* 1974, **64**(11), 1512–1516.
226. Fujii, K., K. Kondo and T. Kasai. *An analysis of the human eye accommodation system.* Osaka University, 1970. pp. 221–236. (Technical Report no. 925. vol. 20.)
227. Bedford, R.E. and G. Wyszecki. Axial chromatic aberration of the human eye. *J. Opt. Soc. Am.* 1957, **47**(6), 564–565.
228. Flitcroft, D.I. A neural and computational model for the chromatic control of accommodation. *Visual Neurosci.* 1990, **5**(6), 547–555.
229. Campbell, F.W. and G. Westheimer. Factors influencing accommodation responses of the human eye. *J. Opt. Soc. Am.* 1959, **49**(6), 568–571.
230. Stark, L.W. and Y. Takahashi. Absence of an odd-error signal mechanism in human accommodation. *IEEE Trans. Bio.-Med. Eng.* 1965, **BME-12**(3 & 4), 138–146.
231. Bobier, W.R., M.C.W. Campbell and M. Hinch. The influence of chromatic aberration on the static accommodative response. *Vision Res.* 1992, **32**(5), 823–832.
232. Wolfe, J.M. and D.A. Owens. Is accommodation colorblind? Focusing chromatic contours. *Perception.* 1981, **10**, 53–62.
233. Switkes, E., A. Bradley and C. Schor. Readily visible changes in color contrast are insufficient to stimulate accommodation. *Vision Res.* 1990, **30**(9), 1367–1376.
234. Kruger, P.B. and J. Pola. Stimuli for accommodation. Blur, chromatic aberration and size. *Vision Res.* 1986, **26**(6), 957–971.
235. Kruger, P.B., S. Mathews, K.R. Aggarwala and S. Nowbotsing. Open-loop accommodation: chromatic and achromatic mechanisms [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1992, **33**(4), 1147.
236. Kruger, P.B., S. Nowbotsing, K.R. Aggarwala and S. Mathews. Small amounts of chromatic aberration influence dynamic accommodation [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1308.
237. Aggarwala, K.R., S. Nowbotsing, S. Mathews and P.B. Kruger. Dynamic accommodation is impaired in narrow band light [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1308.
238. Aggarwala, K.R., P.B. Kruger, S. Mathews, J.H. Park and E.S. Kruger. Spectral bandwidth and accommodative function [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1281.
239. Flitcroft, D.I. The interactions between chromatic aberration, defocus and stimulus chromaticity: implications for visual physiology and colorimetry. *Vision Res.* 1989, **29**(3), 349–360.
240. Ivanoff, A. On the influence of accommodation on spherical aberration in the human eye, an attempt to interpret night myopia. *J. Opt. Soc. Am.* 1947, **37**, 730–731.

241. Atchison, D.A., M.J. Collins and C.F. Wildsoet. Ocular aberrations and accommodation. *Vision Res.* 1994, (in press).
242. Ogle, K.N. *Researches in Binocular Vision.* 2nd printing. New York: Hafner, 1964. pp. 133–134.
243. Rosenfield, M. and B. Gilmartin. Effect of target proximity on the open-loop accommodative response. *Optom. Vision Sci.* 1990, **67**(2), 74–79.
244. Rosenfield, M., J.L. D'Amico, S. Nowbotsing, N. Kapoor and K.J. Ciuffreda. Temporal characteristics of proximally-induced accommodation. *Ophthalmic Physiol. Opt.* 1993, **13**, 151–154.
245. Hennessy, R.T., T. Iida, K. Shiina and H.W. Leibowitz. The effect of pupil size on accommodation. *Vision Res.* 1976, **16**, 587–589.
246. Wick, B. and H.E. Bedell. Magnitude and velocity of proximal vergence. *Invest. Ophthalmol. Visual Sci.* 1989, **30**, 755–760.
247. Wick, B. and D. Currie. Dynamic demonstration of proximal vergence and proximal accommodation. *Optom. Vision Sci.* 1991, **68**(3), 163–167.
248. Kilpatrick, F.P. and W.H. Ittelson. The size-distance invariance hypothesis. *Psychol. Rev.* 1953, **60**(4), 223–231.
249. Alpern, M. Vergence and accommodation, I. Can change in size induce vergence movements? *A. M. A. Arch. Ophthalmol.* 1958, **60**, 355–357.
250. Hennessy, R.T. Instrument myopia. *J. Opt. Soc. Am.* 1975, **65**(10), 1114–1120.
251. Ittelson, W.H. and A. Ames. Accommodation, convergence and their relation to apparent distance. *J. Psychol.* 1950, **30**, 43–62.
252. Kruger, P.B. and J. Pola. Dioptric and non-dioptric stimuli for accommodation: target size alone and with blur and chromatic aberration. *Vision Res.* 1987, **27**(4), 556–567.
253. Judge, S.J. Do target angular size-change and blur cues interact linearly in the control of human accommodation? *Vision Res.* 1988, **28**(2), 263–268.
254. Kotulak, J.C. and S.E. Morse. Perceived distance affects accommodation during binocular viewing if retinotopic cues are reduced [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1281.
255. Takeda, T., T. Iida and Y. Fukui. Dynamic eye accommodation evoked by apparent distances. *Optom. Vision Sci.* 1990, **67**(6), 450–455.
256. Morgan, M.W. Effect of perceived distance on accommodation and convergence. *In: Transactions of the International Ophthalmic Optical Congress.* London: Crosby Lockwood & Son, 1962. pp. 3–15.
257. Hofstetter, H.W. The proximal factor in accommodation and convergence. *Am. J. Optom. Arch. Am. Acad. Optom.* 1942, **19**, 67–76.
258. Alpern, M. Testing distance effects on phoria measurement at various accommodation levels. *A. M. A. Arch. Ophthalmol.* 1955, **54**, 906–915.
259. Gwiazda, J., F. Thorn, J. Bauer and R. Held. Myopic children show insufficient accommodative response to blur. *Invest. Ophthalmol. Visual Sci.* 1993, **34**(3), 690–694.
260. Gwiazda, J., J. Bauer, F. Thorn and R. Held. Is there a "typical" accommodative response function? [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1308.
261. Kotulak, J.C., S.E. Morse and R.W. Wiley. The relative strength of retinotopic and spatiotopic cues to accommodation during instrument viewing [Abstract]. *Optom. Vision Sci., Suppl.* 1993, **70**(12s), 55–56.
262. Ludlam, W.M., S. Wittenberg, E.J. Giglio and R. Rosenberg. Accommodative responses to small changes in dioptric stimulus. *Am. J. Optom. Arch. Am. Acad. Optom.* 1968, **45**(8), 483–506.
263. Campbell, F.W. The depth of field of the human eye. *Opt. Acta (Paris).* 1957, **4**(4), 157–164.

264. Tucker, J. and W.N. Charman. Depth of focus and accommodation for sinusoidal gratings as a function of luminance. *Am. J. Optom. Physiol. Opt.* 1986, **63**(1), 58–70.
265. Tucker, J. and W.N. Charman. Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 137–142.
266. Tucker, J., W.N. Charman and P.A. Ward. Modulation dependence of the accommodation response to sinusoidal gratings. *Vision Res.* 1986, **26**(10), 1693–1707.
267. Hung, G.K., K.J. Ciuffreda and M. Rosenfield. Static model of proximal accommodation and vergence [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1280.
268. Ciuffreda, K.J. and S.C. Hokoda. Spatial frequency dependence of accommodative responses in amblyopic eyes. *Vision Res.* 1983, **23**(12), 1585–1594.
269. Stone, D., S. Mathews and P.B. Kruger. Accommodation and chromatic aberration: effect of spatial frequency. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 244–252.
270. Dul, M., K.J. Ciuffreda and S.K. Fisher. Accommodative accuracy to harmonically related complex grating patterns and their components. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 146–152.
271. Ciuffreda, K.J., M. Dul and S.K. Fisher. Higher-order spatial frequency contribution to accommodative accuracy in normal and amblyopic observers. *Clin. Vision Sci.* 1987, **1**(3), 219–229.
272. Ciuffreda, K.J., M. Rosenfield, J. Rosen, A. Azimi and E. Ong. Accommodative responses to naturalistic stimuli. *Ophthalmic Physiol. Opt.* 1990, **10**, 168–174.
273. Korge, A. and H. Krueger. Influence of edge sharpness on the accommodation of the human eye. *Graefe's Arch. Clin. Exp. Ophthalmol.* 1984, **222**, 26–28.
274. Lowery, H., R. Hall and H. Moores. On dynamic retinoscopy. *Br. J. Physiol. Opt.* 1936, **10**, 49–55.
275. Lovasik, J.V., H. Kergoat and A.C. Kothe. The influence of letter size on the focusing response of the eye. *J. Am. Optom. Assoc.* 1987, **58**(8), 631–639.
276. Tan, R.K.T. and D.J. O'Leary. Steady-state accommodation response to different Snellen letter sizes. *Am. J. Optom. Physiol. Opt.* 1985, **62**(11), 751–754.
277. Owens, D.A. and J.M. Wolfe. Accommodation for flickering stimuli. *Ophthalmic Physiol. Opt.* 1985, **5**(3), 291–296.
278. Neary, C. The effect of high frequency flicker on accommodation. *Ophthalmic Physiol. Opt.* 1989, **9**(4), 440–446.
279. Charman, W.N. and K. Chauhan. Variation in accommodative response with flickering stimuli. *In: Society of Experimental Optometry 1990 Meeting*. Gracie Conference Centre, Moseley, Birmingham: 1990.
280. Ciuffreda, K.J., J. Kellndorfer and D. Rumpf. Contrast and accommodation. *In:* L.W. Stark and G. Obrecht eds. *Presbyopia. Recent Research and Reviews from the Third International Symposium.* New York: Professional Press, 1987. pp. 116–122.
281. Flitcroft, D.I. Effects of temporal frequency on the contrast sensitivity of the human accommodation system. *Vision Res.* 1988, **28**(2), 269–278.
282. Hung, G.K. and K.J. Ciuffreda. Accommodative responses to eccentric and laterally-oscillating targets. *Ophthalmic Physiol. Opt.* 1992, **12**, 361–364.
283. Nadell, M.C. and H.A. Knoll. The effect of luminance, target configuration and lenses upon the refractive state of the eye. Part 2. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**, 86–95.
284. Gu, Y. and G.E. Legge. Accommodation to stimuli in peripheral vision. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1987, **4**(8), 1681–1687.

285. Luria, S.M. and J.S. Kinney. Peripheral stimuli and stereoacuity under water. *Percept. Psychophys.* 1972, **11**(6), 437–440.
286. Semmlow, J.L. and T. Tinor. Accommodative convergence response to off-foveal retinal images. *J. Opt. Soc. Am.* 1978, **68**(11), 1497–1501.
287. Bullimore, M.A. and B. Gilmartin. The influence of retinal areas stimulated on the accommodative response. *In:* A. Fiorentini, D.L. Guyton and I.M. Siegel eds. *Advances in Diagnostic Visual Optics.* Berlin: Springer-Verlag, 1987. pp. 181–185.
288. Hennessy, R.T. and H.W. Leibowitz. The effect of a peripheral stimulus on accommodation. *Percept. Psychophys.* 1971, **10**(3), 129–132.
289. Miege, C. *Etude de la fonction accomodative de l'oeil humain. Application à la correction de la presbytie.* PhD Thesis. Universite de Technologie de Compiegne, 1988. pp. 132–143.
290. Chong, J. and T.J. Triggs. Visual accommodation and target detection in the vicinity of a window post. *Hum. Factors.* 1989, **31**(1), 63–75.
291. Ciuffreda, K.J., N.A. McBrien and S.K. Fisher. Accommodation with and without foveal contribution [Abstract]. *Optom. Vision Sci., Suppl.* 1989, **66**(10), 108.
292. Wertheim, T. Über die indirekte Sehschärfe. *Z. Psychol. Physiol. Sinnesorgane.* 1894, **7**, 172–187.
293. Low, F.N. Peripheral visual acuity. *A. M. A. Arch. Ophthalmol.* 1951, **45**, 80–99.
294. Millodot, M. Foveal and extra-foveal acuity with and without stabilized retinal images. *Br. J. Physiol. Opt.* 1966, **23**(2), 75–106.
295. Le Grand, Y. *Form and Space Vision.* Revised ed. Bloomingtown: Indiana University Press, 1967. pp. 126–145.
296. Millodot, M., C.A. Johnson, A. Lamont and H.W. Leibowitz. Effect of dioptrics on peripheral visual acuity. *Vision Res.* 1975, **15**, 1357–1362.
297. Kelly, D.H. Retinal inhomogeneity. I. Spatiotemporal contrast sensitivity. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1984, **1**(1), 107–113.
298. Pointer, J.S. Visual representation at the cerebral cortex: qualitative and quantitative aspects. *Ophthalmic Physiol. Opt.* 1986, **6**(2), 171–175.
299. Virsu, V. and J. Rovamo. Visual resolution, contrast sensitivity, and the cortical magnification factor. *Exp. Brain Res.* 1979, **37**, 475–494.
300. Rovamo, J. Cortical magnification factor and contrast sensitivity to luminance-modulated chromatic gratings. *Acta Physiol. Scand.* 1983, **119**, 365–371.
301. Banks, M.S. The development of visual accommodation during early infancy. *Child Dev.* 1980, **51**, 646–666.
302. Bullimore, M.A. and B. Gilmartin. Retinal eccentricity and the accommodative response. *Am. J. Optom. Physiol. Opt.* 1987, **64**(8), 644–645.
303. Badal, J. Optomètre métrique international du Dr Badal. Pour la mesure simultanée de la réfraction et de l'acuité visualle même chez les illettrés. *Ann. Ocul.* 1876, **75**(May/April), 101–117.
304. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 88–89; 96–98
305. Takeda, T., Y. Fukui, K. Ikeda and T. Iida. Three-dimensional optometer III. *Appl. Opt.* 1993, **32**(22), 4155–4168.
306. Fisher, S.K. and K.J. Ciuffreda. Accommodation and apparent distance. *Perception.* 1988, **17**, 609–621.

307. Iavecchia, J.H., H.P. Iavecchia and S.N. Roscoe. Eye accommodation to head-up virtual images. *Hum. Factors.* 1988, **30**(6), 689–702.
308. Edgar, G.K., J.C.D. Pope and I. Craig. Visual accommodation with virtual images [Abstract]. *Ophthalmic Physiol. Opt.* 1993, **13**, 435.
309. Ohzu, H. Artificial 3-D displays and visual functions. *In: Vision Science and Its Applications.* Washington, DC: Optical Society of America, 1994. pp. 48–51.
310. Wesner, M.F. and R.J. Miller. Instrument myopia conceptions, misconceptions, and influencing factors. *Doc. Ophthalmol.* 1986, **62**, 281–308.
311. Kotulak, J.C. and S.E. Morse. Is increased accommodation a necessary condition for instrument myopia? *In: Vision Science and Its Applications.* Washington, DC: Optical Society of America, 1994. pp. 113–116.
312. Kotulak, J.C. and S.E. Morse. Relationship among accommodation, focus, and resolution with optical instruments. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1994, **11**(1), 71–79.
313. Smith, G. The accommodative resting states, instrument accommodation and their measurement. *Opt. Acta (Lond.).* 1983, **30**(3), 347–359.
314. Schober, H., H. Dehler and R. Kassel. Accommodation during observations with optical instruments. *J. Opt. Soc. Am.* 1970, **60**(1), 103–107.
315. Kotulak, J.C., S.E. Morse and R.W. Wiley. Accommodation during instrument viewing can be influenced by knowledge of object distance. *In: Vision Science and Its Applications.* Washington, DC: Optical Society of America, 1994. pp. 175–178.
316. Ripps, H., N.B. Chin, I.M. Siegel and G.M. Breinin. The effect of pupil size on accommodation, convergence, and the AC/A ratio. *Invest. Ophthalmol.* 1962, **1**(1), 127–135.
317. Otto, J. and D. Safra. Über das Akkommodationsverhalten hochgradig amblyoper Augen. *Klin. Monatsbl. Augenheilkd.* 1974, **165**, 175–179.
318. Hung, G.K., K.J. Ciuffreda, J.L. Semmlow and S.C. Hokoda. Model of static accommodative behaviour in human amblyopia. *IEEE Trans. Bio.-Med. Eng.* 1983, **BME-30**(10), 665–671.
319. Winn, B. and G. Heron. The temporal accommodation response in amblyopia. *Clin. Vision Sci.* 1990, **5**(2), 157–166.
320. Green, D.G., M.K. Powers and M.S. Banks. Depth of focus, eye size and visual acuity. *Vision Res.* 1980, **20**, 827–835.
321. Leibowitz, H.W. and D.A. Owens. Night myopia and the intermediate dark focus of accommodation. *J. Opt. Soc. Am.* 1975, **65**(10), 1121–1128.
322. Kruger, P.B. Infrared recording retinoscope for monitoring accommodation. *Am. J. Optom. Physiol. Opt.* 1979, **56**(2), 116–123.
323. Kruger, P.B. Changes in fundus reflex luminance with increased cognitive processing. *Am. J. Optom. Physiol. Opt.* 1977, **54**(7), 445–451.
324. Kruger, P.B. The effect of cognitive demand on accommodation. *Am. J. Optom. Physiol. Opt.* 1980, **57**(7), 440–445.
325. Randle, R.J. The non-visual in visual accommodation. *In: International Conference on Cybernetics and Society.* New York: IEEE, 1975. pp. 423–426.
326. Malmstrom, F.V., R.J. Randle, J.S. Bendix and R.J. Weber. The visual accommodation response during concurrent mental activity. *Percept. Psychophys.* 1980, **28**(5), 440–448.
327. Miller, R.J. Mood changes and the dark focus of accommodation. *Percept. Psychophys.* 1978, **24**(5), 437–443.

328. Miller, R.J. and R.C. LeBeau. Induced stress, situationally-specific trait anxiety, and dark focus. *Psychophysiology*. 1982, **19**(3), 260–265.
329. Haynes, H., B.L. White and R. Held. Visual accommodation in human infants. *Science*. 1965, **148**, 528–530.
330. Braddick, O., J. Atkinson, J. French and H.C. Howland. A photorefractive study of infant accommodation. *Vision Res.* 1979, **19**, 1319–1330.
331. Hainline, L., P. Riddell, J. Grose-Fifer and I. Abromov. Development of accommodation and convergence in infancy. *Behav. Brain Res.* 1992, **49**(1), 33–50.
332. Brookman, K.E. Ocular accommodation in human infants. *Am. J. Optom. Physiol. Opt.* 1983, **60**(2), 91–99.
333. Hofstetter, H.W. A longitudinal study of amplitude changes in presbyopia. *Am. J. Optom. Arch. Am. Acad. Optom.* 1965, **42**(1), 3–8.
334. Sun, F., L.W. Stark, V. Lakshminarayanan, J. Wong, A. Nguyen and E. Mueller. Static and dynamic changes in accommodation with age. *In:* L.W. Stark and G. Obrecht eds. *Presbyopia. Recent Research and Reviews from the Third International Symposium*. New York: Professional Press, 1987. pp. 258–263.
335. Ramsdale, C. and W.N. Charman. A longitudinal study of the changes in the static accommodation response. *Ophthalmic Physiol. Opt.* 1989, **9**(3), 255–263.
336. Simonelli, N.M. The dark focus of the human eye and its relationship to age and visual defect. *Hum. Factors*. 1983, **25**(1), 85–92.
337. Whitefoot, H. and W.N. Charman. Dynamic retinoscopy and accommodation. *Ophthalmic Physiol. Opt.* 1992, **12**(1), 8–17.
338. Duane, A. Are the current theories of accommodation correct? *Am. J. Ophthalmol.* 1925, **8**, 196–202.
339. Koretz, J.F. and G.H. Handelman. Modelling age-related accommodative loss in the human eye. *Math. Modelling*. 1986, **7**, 1003–1014.
340. Fisher, R.F. The force of contraction of the human ciliary muscle during accommodation. *J. Physiol.* 1977, **270**, 51–74.
341. Bito, L.Z. and O.C. Miranda. Accommodation and presbyopia. *In:* R.D. Reinecke ed. *Ophthalmology Annual*. New York: Raven Press, 1989. pp. 103–128.
342. Hung, G.K. and K.J. Ciuffreda. Supplementary glossary of control system terminology. *In:* C.M. Schor and K.J. Ciuffreda eds. *Vergence Eye Movements: Basic and Clinical Aspects*. Boston: Butterworths, 1983. pp. 699–703.
343. Riggs, D.S. *Control Theory and Physiological Feedback Mechanisms*. Baltimore: Williams & Wilkins, 1970.
344. Hung, G.K. Adaptation model of accommodation and vergence. *Ophthalmic Physiol. Opt.* 1992, **12**, 319–326.
345. Toates, F.M. A model of accommodation. *Vision Res.* 1970, **10**, 1069–1076.
346. O'Neill, W.D. An interacting control systems analysis of the human lens accommodative controller. *Automatica*. 1969, **5**, 645–654.
347. O'Neill, W.D., C.K. Sanathanan and J.S. Brodkey. A minimum variance, time optimal, control system model of human lens accommodation. *IEEE Trans. Syst. Sci. Cybern.* 1969, **SSC-5**(4), 290–299.
348. Schor, C.M. A dynamic model of cross-coupling between accommodation and convergence: simulations of step and frequency responses. *Optom. Vision Sci.* 1992, **69**(4), 258–269.

349. Semmlow, J.L. Oculomotor responses to near stimuli: the near triad. *In:* B.L. Zuber ed. *Models of Oculomotor Behavior and Control*. Boca Raton, Florida: CRC Press, 1981. pp. 161–191.
350. Mandelbaum, J. An accommodation phenomenon. *A. M. A. Arch. Ophthalmol.* 1960, **63**, 923–926.
351. Hirsch, M.J. Relation of visual acuity to myopia. *Arch. Ophthalmol. (Chic.)*. 1945, **34**, 418–421.
352. Benel, R.A. *Visual Accommodation, the Mandelbaum Effect, and Apparent Size*. PhD thesis. Urbana-Champaign: University of Illinois, 1979.
353. Adams, C.W. and C.A. Johnson. Steady-state and dynamic response properties of the Mandelbaum effect. *Vision Res.* 1991, **31**(4), 751–760.
354. Rosenfield, M. and K.J. Ciuffreda. Accommodative responses to conflicting stimuli. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1991, **8**(2), 422–427.
355. Collins, M., B. Davis and D. Atchison. VDT screen reflections and accommodation response. *Ophthalmic Physiol. Opt.* 1994, **14**, 193–198.
356. Gogel, W.C. Equidistance tendency and its consequences. *Psychological Bulletin*. 1965, **64**(3), 153–163.
357. Eby, D.W. and M.L. Braunstein. The perceptual flattening of 3D scenes enclosed by a frame [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1184.
358. Rogers, B. and M. Graham. Motion parallax as an independent cue for depth perception. *Perception*. 1979, **8**, 125–134.
359. Roscoe, S.N. and J.C. Hull. Cockpit visibility and contrail detection. *Hum. Factors*. 1982, **24**(6), 659–672.
360. National Research Council. Panel on Impact of Video Viewing on Vision of Workers. *Video Displays, Work, and Vision*. Washington, D.C: National Academy Press, 1983. pp. 115–116.
361. Holst, E., von. *The Behavioural Physiology of Animals and Man* [Zur Verhaltensphysiologie bei Tieren und Menschen: Gesammelte Abhandlungen]. translated by R. Martin. London: Methuen, 1973. vol. 1. pp. 185–187; 188–191.
362. Leibowitz, H.W., K. Shiina and R.T. Hennessy. Oculomotor adjustments and size constancy. *Percept. Psychophys.* 1972, **12**(6), 497–500.
363. Enoch, J.M. and R. Nygaard. Retinal strain induced by accommodation: an overview. *In:* L.W. Stark and G. Obrecht eds. *Presbyopia. Recent Research and Reviews from the Third International Symposium*. New York: Professional Press, 1987. pp. 142–146.
364. Smith, G., J.W. Meehan and R.H. Day. The effect of accommodation on retinal image size. *Hum. Factors*. 1992, **34**(3), 289–301.
365. Roscoe, S.N. Bigness is in the eye of the beholder. *Hum. Factors*. 1985, **27**(6), 615–636.
366. Ciuffreda, K.J., M. Rosenfield and L.W. Stark. The role of binocular disparity vergence eye movements in disambiguating superimposed retinal images. *In:* G. Obrecht and L.W. Stark eds. *Presbyopia Research. From Molecular Biology to Visual Adaptation*. New York: Plenum Press, 1991. pp. 217–221. (Perspectives in Vision Research).
367. Barnett, A. Astigmatism: an historical review. *Opt. Dev.* 1944, (December), 2–4.
368. Borish, I.M. *Clinical Refraction*. 3rd ed. Chicago: Professional Press, 1970. pp. 123–148.
369. Millodot, M. Effect of ametropia on peripheral refraction. *Am. J. Optom. Physiol. Opt.* 1981, **58**(9), 691–695.
370. Jalie, M. *The Principles of Ophthalmic Lenses*. 4th ed. London: Association of Dispensing Opticians, 1984. pp. 413–468.
371. Charman, W.N. and H. Whitefoot. Astigmatism, accommodation, and visual instrumentation. *Appl. Opt.* 1978, **17**(24), 3903–3910.

372. Sturm, M. Mémoire sur la théorie de la vision. *C. R. Acad. Sci. Paris.* 1845, **20**, pp. 554–560, 761–767, 1238–1257.
373. Tour, R.L. Astigmatism. *Int. Ophthalmol. Clin.* 1965, **5**, 369–388.
374. Sallman, L. Über das Sehen des Astigmatikers. *Albrecht von Graefe's Archiv für Ophthalmologie.* 1930, **124**, 605–623.
375. Javal, E. Essai sur la physiologie de la lecture. Deuxième partie. Influence de l'éclairage. *Ann. Ocul.* 1878, **80**, 135–147.
376. Freeman, R.D. Asymmetries in human accommodation and visual experience. *Vision Res.* 1975, **15**, 483–492.
377. Fletcher, R.J. Astigmatic accommodation. *Br. J. Physiol. Opt.* 1952, **9**(1), 8–32.
378. Dobson, V., H.C. Howland, C. Moss and M.S. Banks. Photorefraction of normal and astigmatic infants during viewing of patterned stimuli. *Vision Res.* 1983, **23**(10), 1043–1052.
379. Howland, H.C., V. Dobson and N. Sayles. Accommodation in infants as measured by photorefraction. *Vision Res.* 1987, **27**(12), 2141–2152.
380. Mitchell, D.E., R.D. Freeman, M. Millodot and G. Haegerstrom. Meridional amblyopia: Evidence for modification of the human visual system by early visual experience. *Vision Res.* 1973, **13**, 535–558.
381. Rosenfield, M. and K.J. Ciuffreda. Does target orientation influence the accommodative response? *Ophthalmic Physiol. Opt.* 1989, **9**(4), 437–439.
382. Charman, W.N. and J.A.M. Jennings. Objective measurements of the longitudinal chromatic aberration of the human eye. *Vision Res.* 1976, **16**, 999–1005.
383. Cooper, D.P. and P.L. Pease. Longitudinal chromatic aberration of the human eye and wavelength in focus. *Am. J. Optom. Physiol. Opt.* 1988, **65**(2), 99–107.
384. Ivanoff, A. Focusing wave-length for white light. *J. Opt. Soc. Am.* 1949, **39**(8), 718.
385. Millodot, M. and J. Sivak. Influence of accommodation on the chromatic aberration of the eye. *Br. J. Physiol. Opt.* 1973, **28**(3), 169–174.
386. Kellershohn, C., P. Chatelain and H. Roubault. Répartition spectrale d'une source lumineuse et accommodation de l'oeil. *C. R. Séances Soc. Biol. Fil.* 1957, **151**, 985–987.
387. Charman, W.N. Accommodation performance for chromatic displays. *Ophthalmic Physiol. Opt.* 1989, **9**(4), 459–463.
388. Krueger, H. and R. Mader. Der Einfluß der Farbsättigung auf den chromatischen Fehler der Akkomodation des menschlichen Auges. *Fortschr. Ophthalmol.* 1982, **79**(2), 171–173.
389. Murch, G.M. Visual accommodation and convergence to multichromatic information displays. *In: SID International Symposium. Digest of Technical Papers.* 1982. vol. 13. pp. 192–193.
390. Stoddard, K.B. and M.W. Morgan Jr. Monocular accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1942, **19**, 460–465.
391. Marran, L. and C.M. Schor. Retinal and extraretinal cues to nonconjugate accommodation [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1994, **35**(4), 1736.
392. Flitcroft, D.I., S.J. Judge and J.W. Morley. Binocular interactions in accommodation control: effects of anisometropic stimuli. *J. Neurosci.* 1992, **12**(1), 188–203.
393. Kotulak, J.C. and S.E. Morse. The accommodative response when the dioptric stimuli to the two eyes conflict [Abstract]. *Optom. Vision Sci., Suppl.* 1993, **70**(12s), 150.
394. Rosenberg, R., N. Flax, B. Brodsky and L. Abelman. Accommodation levels under conditions of asymmetric convergence. *Am. J. Optom. Arch. Am. Acad. Optom.* 1953, **30**(5), 244–254.

395. Spencer, R.W. and W.K. Wilson. Accommodative response in asymmetric convergence. *Am. J. Optom. Arch. Am. Acad. Optom.* 1954, **31**, 498–505.

Chapter 2

Research Topics

The review of the previous chapter has indicated many aspects of the accommodation response for which either little or nothing is known, or for which previous studies conflict. I investigate some of these topics in my research.

I investigate the effects of subject instruction on accommodation because their effects have not previously been systematically investigated even though there are indications that they can markedly affect the accommodation response (Chapter 3). I study the effects of instructions because it is important to know that the instructions used in a study do not bias subjects' accommodation responses in a particular way. I also compare accommodation responses for targets presented in real space and in a Badal optical system (Chapter 3). Even though Badal optical systems are used widely in accommodation research, it has not been shown that the accommodation responses of subjects to targets in these systems are the

same as when viewing targets in real space. Thus it is uncertain whether results obtained with Badal systems can be applied to viewing in real scenes.

Previous studies of the effect of pupil size on fluctuations of accommodation are conflicting so I repeat these experiments to see if either of their findings can be replicated (Chapter 4). I also use two accommodation stimulus levels to see how the mean accommodation response level and the pupil size interact to affect the fluctuations of accommodation.

Previous studies of peripheral stimuli to accommodation have used targets that may have encouraged voluntary accommodation, so it is not known whether 'reflex' responses of accommodation can occur to the blur of peripheral targets. In my research I use central and peripheral targets moving in depth to investigate the roles of 'reflex' and voluntary accommodation (Chapter 5). I use sinusoidal target motion to reduce voluntary accommodation effects. If a suitably high speed of target motion is used then the subject has no time to make voluntary trial-and-error hunting movements of accommodation. The subject may intermittently make a voluntary focus change in the correct direction, but the sinusoidal motion is too fast for the subject to consistently make synchronous voluntary changes in focus. I hypothesise that if accommodation occurs for slowly moving peripheral targets but not for quickly moving peripheral targets then this would suggest that subjects use voluntary accommodation to focus on slowly moving peripheral targets. I also extend the control system models currently used for single, central targets to the case of peripheral and complex targets. In particular I wish to see if the accommodation responses to extended targets can be predicted from the accommodation responses to their constituent parts (Chapter 5).

Present research seems to indicate that it is difficult to predict the accommodation responses to conflicting targets. However, a review of the literature shows several factors which may explain this variability.

Firstly, many studies of accommodation responses to conflicting targets did not instruct the subjects to attend to one particular target of a conflicting target pair. Subjects in these studies may have attended and focused to either

of a conflicting target pair. To reduce this potential source of variability I use instructions in my studies that require subjects to attend to one particular target (Chapters 6, 7 & 8).

It is possible that people use voluntary accommodation to overcome unwanted responses to conflicting targets, so I investigate whether they use a particular type of voluntary accommodation: memorised voluntary accommodation (Chapters 6 & 7). I hypothesise that people may overcome the Mandelbaum effect by locking on to a remembered focus level appropriate for the known distance of the attended target.

Another factor in the accommodation responses to conflicting targets that I investigate is the upper blur threshold (Chapter 8). I hypothesise that if a conflicting target is beyond the upper blur threshold then it will not provide a stimulus to accommodation. I also hypothesise that the prior adapting level of accommodation may bias the response to conflicting targets (Chapter 8). For example, if a subject adapts at the same stimulus level as a conflicting target, then this conflicting target may capture their focus and prevent them from accommodating to another attended target.

I also extend the control models currently used for single targets to the case of multiple targets (Chapter 8). These control models represent in a quantitative way a number of hypothesised response patterns to conflicting targets. I compare the performance of alternative models to see which performs best at predicting accommodation responses to conflicting targets.

Chapter 3

Subject Instructions and Methods of Target Presentation in Accommodation Research*

3.1. Introduction

This study investigates the potential of subject instructions to alter the static accommodative stimulus–response function. The study also investigates whether the reduced cue environment of the Badal optical system leads to accommodation responses different from those that occur for targets presented in real space.

* This chapter is adapted with permission of the publishers from: Stark, L.R. and D.A. Atchison. Subject instructions and methods of target presentation in accommodation research. *Invest. Ophthalmol. Visual Sci.* 1994, 35(2), 528-537.

Subject Instructions

Within the field of accommodation research, interest in subject instructions developed after various studies of the spatial frequency response function of accommodation yielded widely conflicting results.[1-5] Owens suggested that subject instructions may account for some of these differences.[3] Ciuffreda and Hokoda demonstrated that instructions could markedly affect the accommodation response to static sinusoidal gratings.[6] While viewing grating targets at a stimulus level of 6 D, the responses of a single experienced subject varied by up to 3.5 D between instructions. Thus it would appear that instructions, acting through voluntary or higher order control, have the potential to significantly alter the accommodation response (see section 1.5.8.1)

However the effects of subject instructions on the static accommodation stimulus–response function have not yet been systematically investigated. If the aim of a particular study is to determine how people normally accommodate in a given situation, it would be important to know that the subject instructions are not significantly biasing the response in a particular direction.

Methods of Target Presentation

Optical presentation of targets is popular in accommodation research, and systems based on the Badal principle[7,8] are common. However no research has yet demonstrated that response functions for Badal targets are identical to those for targets presented in real space. The Badal system removes a number of the monocular depth cues which, through proximal accommodation, play a role in directing the overall accommodation response (see sections 1.4.2 & 1.5.5.1).[9] In a Badal system the retinal image of the target does not increase in size as it moves towards the subject. Other depth cues[10] such as object overlay, perspective, areas of light and shade, and object height are absent in the Badal system. Furthermore, the awareness of the physical proximity of an object may affect the accommodation response, irrespective of its dioptric distance. For example, the instrument

myopia suffered by microscope users has been partly attributed to the users accommodating for what they believe is a close object (see section 1.5.5.4).[11] Apart from the possibility of small biases in the response with Badal targets, there have been incidental reports of definite subject difficulties in Badal systems, interestingly for both experienced and inexperienced subjects.[12-15]

3.2. Methods

Subjects

Thirty-five adolescents and young adults (age range 15 to 27 years) participated as subjects in the study. They were first year optometry students, non academic staff members of the university, and members of the general public. None had previous experience as subjects in accommodation research, and all were unaware of the true purpose of the experiment. An awareness that accommodation was being measured may have biased the responses. Subjects were initially told the purpose of the study was to investigate eyestrain and visual tasks. Throughout the experiment subjects had to rate a number of asthenopic complaints on a 1 to 5 scale, and also make measurements of near heterophoria using a Maddox wing.

One subject participated in a pilot run of the experiment using the original protocol. Thirty-four subjects participated in the study proper with a final (but modified) protocol, although only data collected for twenty-four of these subjects could be used in the analysis. Five subjects were excluded because of errors implementing the protocol. Five more subjects were excluded because of high spurious cylinder values in the Canon Autoref readings attributed to: corneal irregularity (one subject), moderate to high myopia (two subjects), or unknown origin (two subjects).

Distance monocular visual acuities measured with a wall chart were 6/7.5 or better in both left and right eyes. One subject had good acuity in her right eye (6/5) but poorer acuity in her left eye (6/7.5), and was excluded from a comparison of binocular and monocular responses. Mean best sphere refractions ranged between -4.4 D and +0.8 D. Cylindrical components were

1.25 DC or less. Amplitudes of accommodation by a subjective push-up method were sufficient for the tasks involved: 7.5 D or better in the right eye and 8 D or better binocularly.

Apparatus

The accommodation response was measured using a Canon Autoref R-1 infra-red optometer operating in its standard mode (see Appendix A).[16] This instrument allows an open field of view approximately 23° high by 50° wide, although intrusions in the inferior field come to within 8° of fixation. The refraction readings provided by the Canon were calibrated against subjective refraction in separate experiments (see section A.2). The mean calibration equation thus obtained was used to modify all later experimental Canon Autoref readings.

A calibrated scale was used to measure horizontal pupil diameters from a monitor displaying an image of the subject's right eye.

All targets had the same general form and angular dimensions regardless of presentation method or stimulus distance. The target was a block of high contrast text, 5° wide, set in Times Roman font. A letter height of 6/15 Snellen equivalent was used. The letter size was chosen to provide fine spatial detail at a few lines above acuity threshold. Gaze shifts within the 5° block of text were found in a preliminary experiment to have negligible effects on Autoref readings (see section A.3). A black surround field (22° × 24°) screened surrounding objects from view. All targets were set to a luminance of approximately 15 $cd.m^{-2}$ which is sufficient to allow an accurate response function.[17]

Targets were constructed for presentation in real space at nominal target distances of 2 m (0.5 D), 50 cm (2 D), 25 cm (4 D) and 16.7 cm (6 D), all based on the above described dimensions. An optical stimulus presentation system based on the Badal principle was mounted on top of the Canon Autoref to present targets at similar stimulus levels as those presented in real space (Figure 3.1). The system was non-Maxwellian view and provided accommodation stimuli referenced to an arbitrary entrance pupil 3.05 mm

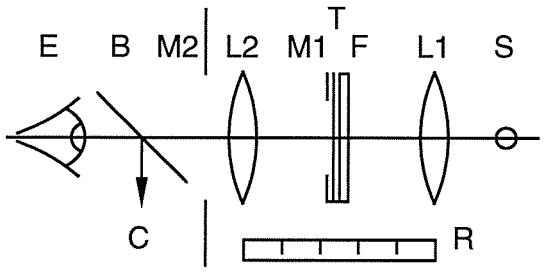


Figure 3.1. The Badal stimulus system. The various components are: incandescent globe (S); condensing lens (L1); translucent perspex sheet (F); letter target (T); black surround field of the target (M1); Badal lens: an achromat, F_e = +7.14 D (L2); mask to prevent view of apparatus by subject (M2); scale to indicate target position (R); infra-red beam splitter of Canon Autoref (B); Canon Autoref (C); subject's eye (E). M1, T, and F are held in apposition but are shown separated for clarity. The anterior focal point of the Badal lens is placed at the entrance pupil of the subject's right eye.

behind the corneal vertex. Normal Autoref alignment procedures automatically placed the anterior focal point of the Badal lens very close to this arbitrary entrance pupil. I used a ophthalmic trial lenses and a telescope adjusted for the distance refractive error of my eye to determine the actual stimulus level at each nominal target setting for both the real space and Badal targets.

Procedures

A pilot run of the experiment was initially performed with one subject. This subject had difficulties relaxing focus to the 0.5 D Badal target after first focusing to the higher stimulus levels. As a precaution the original protocol was modified to present targets always in ascending order of stimulus level.

Subjects wore their measured subjective refraction throughout the experiment either as ophthalmic trial lenses, or as contact lenses with a trial lens over-refraction. Generally for cylindrical components of less than 0.50 DC, a best sphere correction was worn. With full subjective refractions in place, targets could be placed at set stimulus levels for all subjects. Lens

effectivity was negligible for all but one subject with myopia (subject 8, right eye refractive error -3.9 DS), and was not considered in later calculations. Comparisons between conditions would have still been valid for this subject. Natural pupil sizes were used throughout and ranged between 2.7 mm and 8.4 mm horizontal diameter in the right eye depending on the particular subject and stimulus distance. Average minimum and maximum pupil sizes were 4.2 mm and 6.6 mm respectively.

Measurements of the accommodation response to real space targets were first made under both binocular and right eye monocular viewing conditions with the *baseline instruction*:

> pick a word in the middle of the block of text and look at it.

This instruction was required for stabilisation of gaze and subsequent measurement of accommodation with the Autoref. The responses recorded with this instruction were used as baselines against which the effects of three focusing instructions could be compared (see below). The order of testing under monocular and binocular conditions was counterbalanced between subjects.[18] Five to ten readings of accommodation were taken from the right eye at each stimulus level in the experiment.

The baseline instruction to 'pick a word in the middle of the block of text and look at it' was the minimum required to control gaze and allow measurements to be made with the Autoref. Whether the responses recorded with this baseline instruction are identical to those which occur in the real world is unknown, although to obtain measures of the accommodation response in a surreptitious manner would be extremely difficult. The response functions so recorded would be dependent on the task being performed at the time and on other cognitive factors,[19] so it is unlikely that any one response function could be established as the truly 'normal' response. Considering these arguments, the baseline responses of this experiment approximate the normal responses expected from naive subjects

when participating in accommodation research and when provided with a minimal instruction to stabilise gaze.

Each subject was then introduced to a particular instruction, of which there were three; one instruction for each group of 8 subjects. Each subject was allocated to a group based on order of presentation. Instructions were stated to the subject almost verbatim and without elaboration. To avoid the possibility of differential carry-over effects,[20] each subject received only one of the three instructions.

Subjects in Group 1 received *Instruction 1*:

> For the rest of this experiment I want you to look at the words but make no special effort to focus on them. Let your eyes relax and let them choose a focus.

This was a modification of an instruction used by Owens in the study of the Mandelbaum effect.[21] Subjects in Group 2 received *Instruction 2*:

> For the rest of this experiment I want you to look at the words naturally, the same as you would when normally reading a book or sign at the same distance.

This was a modification of instructions used by Owens[3] and Ciuffreda and Hokoda.[5] Subjects in Group 3 received *Instruction 3*:

> For the rest of this experiment I want you to look at the words and carefully focus on them so that they are maximally sharp and clear at all times. Do not let the words become blurred by the slightest amount at any time.

This was a modification of instructions used by Charman and Tucker[2] and Ciuffreda and Hokoda.[6]

The results of this study should not be taken as indicative of the usefulness of the original source instructions. In the cases of Instructions 1 and 3, significant changes were made to the original sources in an attempt to increase anticipated differences in accommodation responses. Also, the

source for Instruction 1 was only ever intended for use in a specific situation — the study of the Mandelbaum effect.[21,22]

The right eye monocular accommodation response was then measured for targets presented in real space and in the Badal system at the various stimulus levels. Presentation method order (real space or Badal) was counterbalanced between subjects.[18] The instructions were repeated intermittently throughout the experiment.

At the conclusion of the experiment, subjects were questioned regarding their believed ability to alter focus voluntarily and about whether they had been consciously altering focus during the latter part of the experiment.

Analysis

Spherocylindrical readings from the Canon Autoref were converted to best sphere values and a mean of useable readings calculated. Readings with cylindrical components greater than 0.75 DC were discarded. The mean Autoref readings were converted to an accommodation response referred to an arbitrary principal plane 1.55 mm behind the corneal vertex, using the calibration equation previously obtained (see section A.2).

Accommodation error was used as the dependent variable in all analyses, and was obtained by subtracting the accommodation stimulus from the accommodation response. Three analyses of variance were performed; the first for all three groups as a whole, the second for Group 1 separately, and the third analysis for Groups 2 and 3 taken together. The decision to perform a number of separate analyses of variance was based on the results of post hoc comparisons from the analysis involving all three groups (see Results). Analyses of variance variously used the between-subjects factor of Subject Group (three levels: group one, group two, group three), and the two within-subject factors of Viewing Condition (four levels: baseline real space binocular; baseline real space monocular; real space monocular with focusing Instruction 1, 2 or 3; Badal monocular with focusing Instruction 1, 2 or 3) and Stimulus Level (four levels: 0.5 D, 2 D, 4 D, 6 D). Note that the factor of Subject Group is not interchangeable in meaning with 'Instruction'.

This is because the focusing instructions were only applied to the last two Viewing Conditions: in the first two Viewing Conditions the baseline instruction was used. Although there were small differences between nominal and actual stimulus levels (for a nominal 6 D stimulus, the target in real space was at 6.125 D, and for Badal viewing it was at 5.875 D), these differences were ignored for simplicity of analysis, and the nominal stimulus used as a categorical variable.

In an effort to control the experiment-wise error rate and to retain statistical power, only those post hoc comparisons answering specific questions were tested. In determining the significance of a result, an approach recommended by Keppel was followed.[20] If a comparison was not significant at the uncorrected 0.05 level, then the null hypothesis was retained. If a comparison was significant even at the stringent Bonferroni corrected level of 0.0033 then the null hypothesis was rejected. However if the significance of a comparison fell between the corrected and uncorrected significance levels (i.e. $0.05 > p > 0.0033$), then judgement was withheld.

3.3. Results

All Subjects

Mean baseline stimulus–response functions demonstrated the classic form,[23] having a lead of accommodation at the lower stimulus levels and a lag at the higher stimulus levels (Figure 3.2). Baseline binocular and monocular responses were not significantly different from each other (Figure 3.2 & Table 3.1, comparison 1), in agreement with previous research.[24]

There were significant differences in the responses between Groups 1, 2 and 3 (ANOVA, $F_{2,21} = 10.8$, $p < 0.0006$), but these trends were complicated by significant interactions between the factors of Subject Group, Viewing Condition and Stimulus Level (ANOVA, Viewing Condition × Subject Group, $F_{6,63} = 13.2$, $p < 0.0001$; Stimulus × Subject Group, $F_{6,63} = 17.8$, $p < 0.0001$; Viewing Condition × Stimulus, $F_{9,189} = 10.4$, $p < 0.0001$; Viewing Condition × Stimulus × Subject Group, $F_{18,189} = 13$, $p < 0.0001$).

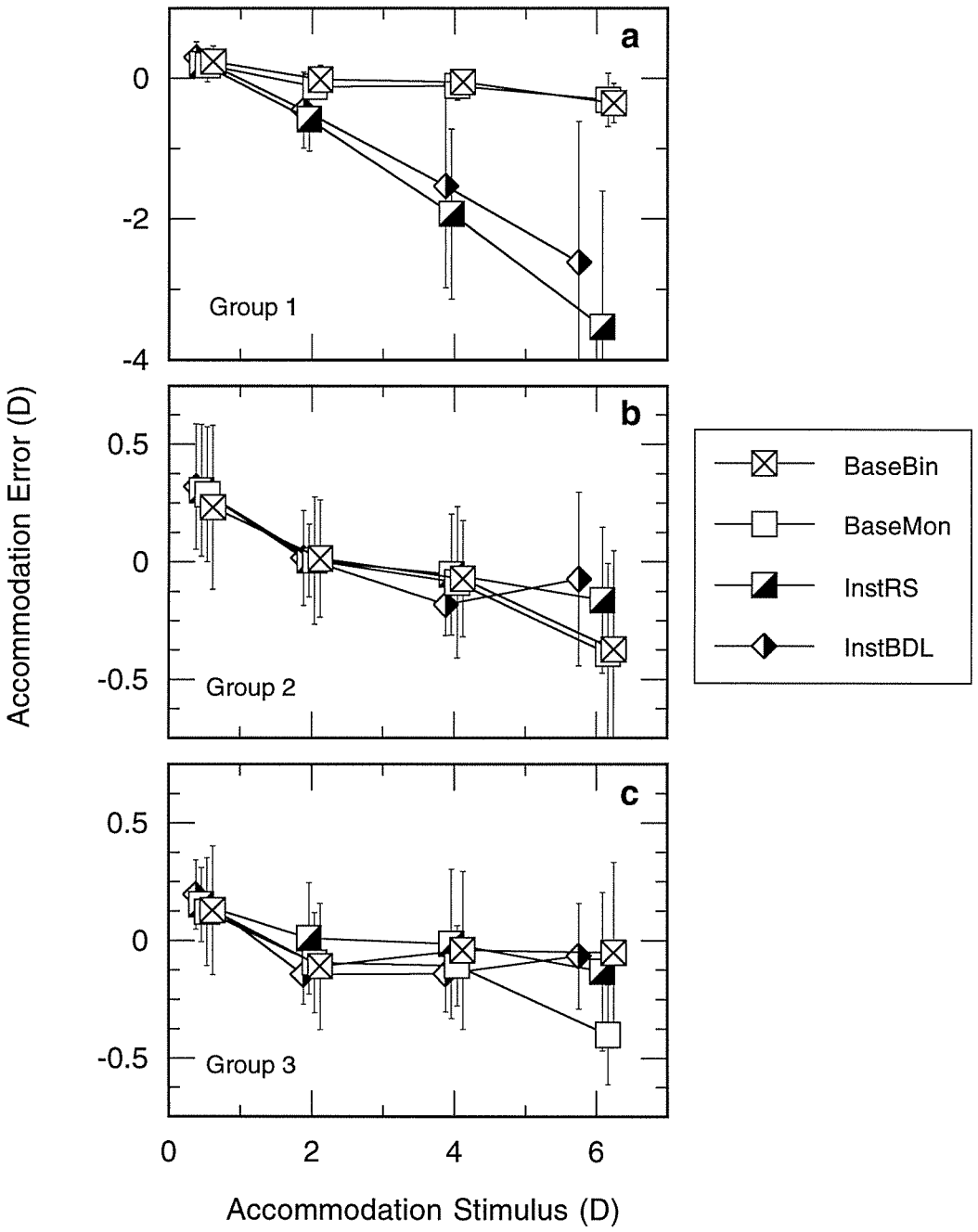


Figure 3.2. Mean accommodation error as a function of stimulus for (**a**) Group 1 (n = 8), (**b**) Group 2 (n = 8), and (**c**) Group 3 (n = 8). Groups 1, 2, and 3 received Instructions 1, 2, and 3, respectively in the non-baseline conditions. Note differences in scale between various ordinates. All plots have been staggered along the abscissae for clarity. Error bars represent between-subject variability and denote ± 1 SD. BaseBin: Real space binocular response with baseline instruction. BaseMon: Real space right eye monocular response with baseline instruction. InstRS: Real space right eye monocular response with Instruction 1, 2, or 3. InstBDL: Badal system right eye monocular response with Instruction 1, 2, or 3.

Table 3.1. Post hoc comparisons (single degree of freedom)

Comparison N°	*Group(s)*	*Comparison*	*Qualifications*	*F*	*p*
1	All	BaseBin vs BaseMon	All stimulus levels	0.27	0.60
2	2, 3	Group 2 vs Group 3	All viewing conditions & stimulus levels	0.04	0.85
3	All	Group 1 vs (Group 2 & Group 3)	All viewing conditions & stimulus levels	21.6	0.0001*
4	2, 3	InstRS vs Base	All stimulus levels	13.1	0.0004*
5	2, 3	InstBDL vs Base	All stimulus levels	6.1	0.015†
6	2, 3	(InstRS & InstBDL) vs Base	At 6 D	35.8	0.0001*
7	2, 3	(InstRS & InstBDL) vs Base	At 0.5, 2, and 4 D	0.72	0.40
8	2, 3	InstRS vs InstBDL	All stimulus levels	1.0	0.32
9	1	InstRS vs Base	All stimulus levels	123	0.0001*
10	1	InstBDL vs Base	All stimulus levels	64.4	0.0001*
11	1	(InstRS & InstBDL) vs Base	At 6 D	179	0.0001*
12	1	(InstRS & InstBDL) vs Base	At 4 D	64.5	0.0001*
13	1	(InstRS & InstBDL) vs Base	At 2 D	4.75	0.033†
14	1	(InstRS & InstBDL) vs Base	At 0.5 D	0.039	0.84
15	1	InstRS vs InstBDL	All Stimulus levels	7.0	0.01†

* Differences significant at the Bonferroni corrected level ($p < 0.0033$). † Differences falling between the uncorrected and corrected significance levels ($0.05 > p > 0.0033$) and for which judgement was reserved. BaseBin: Baseline real space binocular response (with baseline instruction). BaseMon: Baseline real space right eye monocular response (with baseline instruction). Base: Average of baseline real space binocular and real space monocular responses. InstRS: Real space right eye monocular response with Instruction 1, 2, or 3. InstBDL: Badal system right eye monocular response with Instruction 1, 2, or 3.

Mean responses in Groups 2 and 3 were not significantly different from each other, but when taken as a pair they were significantly different from

the responses observed in Group 1 (Table 3.1, comparisons 2 & 3). Confidence intervals were constructed for the true difference in mean response functions with Instructions 2 and 3. An average of the baseline binocular and monocular responses was subtracted from the real space or Badal response, and this parameter (the 'difference from baseline') used to compare Instructions 2 and 3. (An average of the baseline binocular and monocular responses was used as it was thought it would provide a more stable estimate of the baseline response level. This averaging procedure is valid because there is no significant difference between binocular and monocular responses, as shown by comparison 1 in Table 3.1.)

There appeared to be no systematic differences between mean response functions for Instructions 2 and 3, although differences of up to 1 D were possible for any given stimulus level:

Confidence intervals for the differences in means.

Mean Instruction 3 'difference from baseline' less mean Instruction 2 'difference from baseline' and associated 95% confidence intervals (dioptres).

Real space viewing

at 0.5 D, 0.0 ± 0.22

at 2 D, 0.12 ± 0.26

at 4 D, 0.03 ± 0.2

at 6 D, 0.19 ± 0.76.

Badal viewing

at 0.5 D, 0.0 ± 0.16

at 2 D, -0.05 ± 0.22

at 4 D, 0.03 ± 0.21

at 6 D, -0.15 ± 0.31.

Groups 2 & 3

Instruction 2 and Instruction 3 had almost negligible effects on the accommodation response function (Figures 3.2b, 3.2c). However for real space viewing these small differences from the baseline were statistically

significant (Table 3.1, comparison 4). For Badal system viewing, differences from the baseline were equivocal (Table 3.1, comparison 5). Real space and Badal responses, taken together, did not differ significantly from the baseline responses at 0.5, 2 and 4 D, but at 6 D responses with Instructions 2 and 3 were significantly more accurate than the baseline responses by about 0.20 D (Figures 3.2b, 3.2c, & Table 3.1, comparisons 6 & 7). For Groups 2 and 3 taken together, real space and Badal responses were not significantly different from each other (Table 3.1, comparison 8). Confidence intervals demonstrate that for normal experimental purposes, response functions to real space and Badal targets were identical:

Confidence intervals for paired observations.

Mean values of real space response less Badal response, and associated 95% confidence interval (dioptres)

at 0.5 D, -0.03 ± 0.06

at 2 D, 0.07 ± 0.10

at 4 D, 0.13 ± 0.14

at 6 D, -0.08 ± 0.10.

Group 1

With Instruction 1, many subjects adopted lags of accommodation that increased with stimulus level (Figure 3.2a). Responses for both real space viewing and Badal system viewing under Instruction 1 differed significantly from the baseline responses, and this effect was most noticeable at the higher stimulus levels, equivocal at 2 D, but not significant at 0.5 D (Table 3.1, comparisons 9–14). There were equivocal differences between real space and Badal viewing responses (Table 3.1, comparison 15), but the presence of large within-subject variability observed in a few subjects must temper these findings.

Between-subject differences under Instruction 1 were large (Figure 3.3), but three natural clusters of subjects were evident based on the slopes of the stimulus–response functions. Subjects in the first cluster (subjects 3, 9, 15 & 18) consistently relaxed their accommodation towards some intermediate

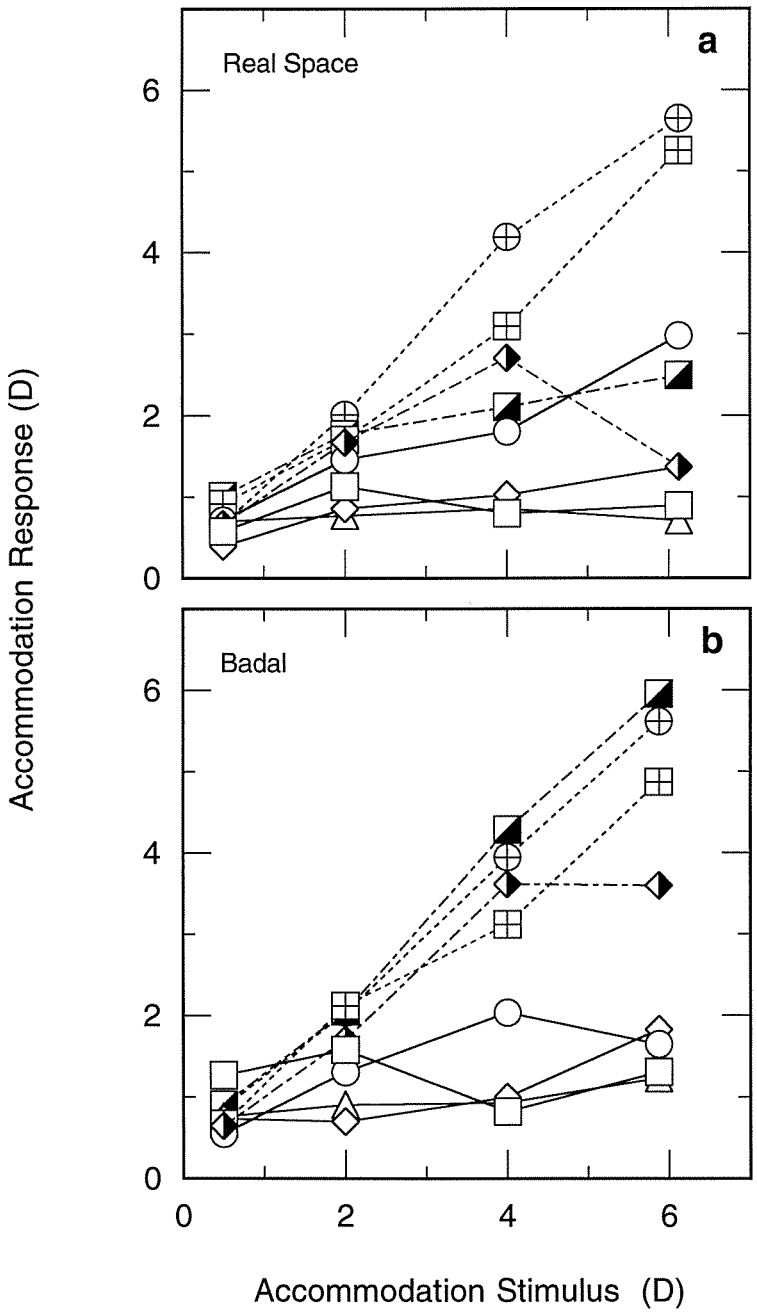


Figure 3.3. Individual response functions for subjects in Group 1 (n = 8) while viewing (**a**) targets in real space and (**b**) Badal targets. Subjects received Instruction 1. Subjects in Cluster 1 (solid lines, subjects 3, 9, 15, 18) consistently relaxed accommodation. Subjects in Cluster 2 (dotted and dashed lines, subjects 6 & 21) were inconsistent in their responses, and subjects in Cluster 3 (dotted lines, subjects 12 & 24) maintained accurate accommodation. Key: subject 3 (hollow squares), subject 6 (half filled diamonds), subject 9 (hollow circles), subject 12 (crossed squares), subject 15 (hollow diamonds), subject 18 (hollow triangles), subject 21 (half filled squares), subject 24 (crossed circles).

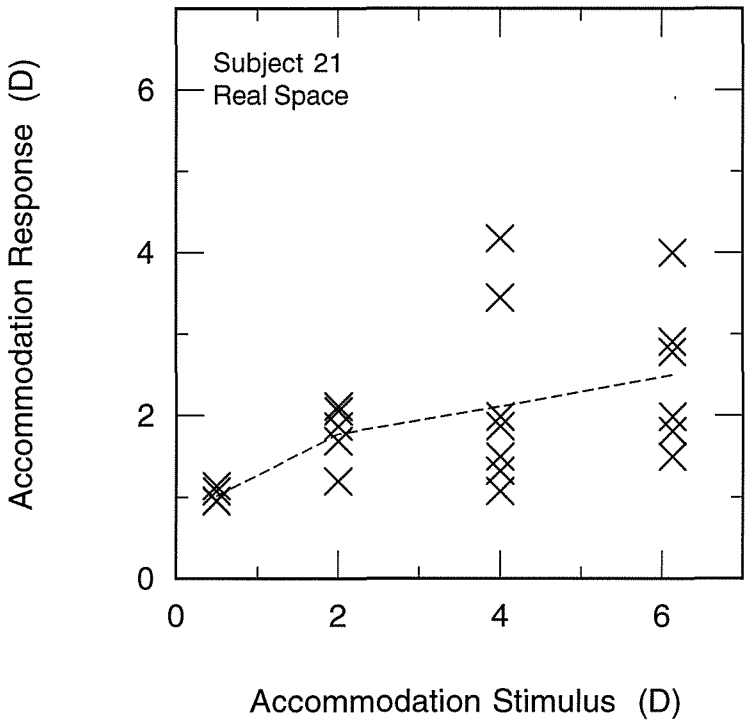


Figure 3.4. Highly variable accommodation response of a single subject (N° 21) with Instruction 1. The target was presented in real space. The mean response function is denoted by a dashed line. Some plot symbols overlap.

value. Subjects in the second cluster (subjects 6 & 21) were inconsistent in their responses between real space and Badal viewing, while subjects in the third cluster (subjects 12 & 24) consistently maintained accurate accommodation. Some subjects in Group 1 demonstrated responses that fluctuated widely (Figure 3.4).

3.4. Discussion

Subject Instructions

All three instructions affect accommodation to some extent. Responses with Instruction 2, 'view the target naturally', and Instruction 3, 'focus carefully' are not significantly different. However responses with Instruction 1, 'make no special effort', are significantly different from responses with Instructions 2 and 3.

Response functions with Instruction 2, 'view the target naturally', and Instruction 3, 'focus carefully', are not significantly different from each other, although they both differ slightly from the baseline responses. In this study, Instruction 3 did not lead to an increased accommodation response compared with Instruction 2. In contrast Ciuffreda and Hokoda[6] thought for sinusoidal gratings that an instruction to 'obtain the best possible focus' (similar to this study's Instruction 3) would lead to voluntary positive accommodation and an increased accommodation response, while the instruction to 'focus all targets naturally, without straining' (similar to this study's Instruction 2) would lead to a reduced response. Previous studies of the accommodation response with sinusoidal gratings generally demonstrate considerable lags or leads in the response, thus providing some latitude for voluntary accommodation to obtain a more accurate response. On the other hand, baseline responses in this study were quite accurate, and if extra voluntary accommodation was brought into play in an effort to consciously maximise target contrast, then its effect was probably too small to be reliably detected.

There is another explanation for the similarity between responses under Instructions 2 and 3. It may be that the subjects in Group 2 of this study normally focus carefully at objects (as in Instruction 3). So when instructed to 'look at the words naturally', subjects in Group 2 may have been focusing carefully, the same as those subjects in Group 3 who were instructed to 'carefully focus'.

The mean responses with Instructions 2 and 3 for targets at 6 D demonstrated about 0.20 D less accommodation lag than for the baseline responses. This small effect could be due to a time order effect, as the responses with focusing instructions were always recorded after the baseline responses, and the 6 D responses were always recorded after those for the other stimulus levels.

The subjects' perceptions of their own responses provide an insight into the types of voluntary accommodation used under the various instructions. When provided with Instructions 2 and 3, subjects in Groups 2 and 3

described their responses variously as focusing on the words, keeping the letters clear, looking at the words or concentrating on the words. However two subjects in Group 3 also reported making conscious adjustments in their focus whenever they noticed any blur. Of the sixteen subjects in Groups 2 and 3, five reported transient blurring of the target, while a further 4 subjects made general statements on target clarity.

Four subjects in Group 1 maintained flat response profiles with Instruction 1, 'make no special effort' (Figure 3.3, Cluster 1). Of these four subjects, three perceived they were making some change in their accommodation, describing it as either relaxing the eyes (subject 15), allowing the words to go blurred (subject 18), or not focusing on the letters (subject 3). However one subject (subject 9) while stating no conscious control over accommodation, maintained a reasonably flat response profile nevertheless. She stated that most of the targets were blurred in any case, and to see them clearly would have required concentration. She was obviously suspending normal attention to the target, but was unable to adequately verbalise her actions: an inability similar to that reported in another study.[25] The subjects in Group 1 with variable responses under Instruction 1 (Figure 3.3, Cluster 2) described their attempts to relax focus as either relaxing the eyes (subject 21) or not focusing on the letters (subject 6). Finally, the two subjects in Group 1 who maintained accurate responses under Instruction 1 (Figure 3.3, Cluster 3) made some interesting observations. Subject 12 stated she was maintaining steady gaze on a word, while attempting not to take notice of the word. This indicates an attempt to suspend normal attention to the accommodation target. Subject 24 said she was able to accommodate voluntarily but was not doing so in the experiment. She may have interpreted the instruction as requiring accommodation to the target but without 'special effort.' Because several other subjects under Instruction 1 relaxed their focus, some of the variability between subjects may be due to differing interpretations of the instruction. Six subjects in Group 1 described target clarity (or blur) during the

experiment, and these reports matched the objective accommodation responses in every case.

Some subjects in Group 1 adopted stimulus–response functions with greatly reduced slopes when given Instruction 1 (Figure 3.3). Using a simple blur based (retinotopic) control model of accommodation this would correspond to a reduction of accommodation controller gain. However a model such as this ignores the role proximal factors are likely to play in directing the accommodation response.[9] When viewing a target in real space, a flat response function would require suppression of both the retinotopic (blur based) system and the spatiotopic (proximal based) system. An attentional mechanism may direct this process. Attention voluntarily directed away from an object may, in this explanation, render its depth cues unavailable to the spatiotopic system, and also actively suppress controller gain in the retinotopic system. Attention can be actively redirected from centrally viewed targets during a cognitive task.[26] Furthermore, at least two subjects in this study (subjects 9 & 12) suspended attention to the target to relax accommodation. Alternatively, a rigid accommodation posture may be maintained either through true voluntary accommodation, or secondarily through voluntary convergence. True voluntary accommodation cannot be ruled out in the subjects of this study. However, accommodation driven by voluntary convergence is unlikely as it is accommodation that appears to drive the voluntary near response.[25]

Francis *et al.*[27] have previously made a distinction between voluntary accommodation and 'effort to see'. This study supports their concept that there are at least two voluntary processes involved in oculomotor control, namely, attention to a target (which can be initiated, maintained or suspended), and the more active 'true' voluntary accommodation.

Instructions 2 and 3 lead to responses close to those which occur normally (i.e. baseline responses) except perhaps at high stimulus levels where they may lead to a more accurate response. Instructions 2 and 3 (or variants of these) can be recommended for accommodation research, but with a number of provisos based on considerations from other studies. This

study used well illuminated, high contrast, broad spatial frequency band targets, and pupil sizes were relatively large (4.2–6.6 mm, on average). For these conditions accommodation is quite accurate over a large range of stimulus distances. However, where there is normally any significant inaccuracy in the response function, Instructions 2 and 3 may have different effects. For sine wave gratings there is normally a lag of accommodation, and the instruction to 'carefully focus' can lead to positive voluntary accommodation.[6] By extension Instruction 3 is probably better avoided in cases where there are normally inaccuracies of accommodation, for example, low luminance,[17] targets of very poor contrast,[28] small pupil sizes,[29] and amblyopia.[30]

Letter size and target form may interact with the subject instructions (section 1.5.1.3). For example, if large letters are used as targets then some subjects may normally (as in Instruction 2) accommodate only enough to resolve the letters, as suggested by Charman and Tucker.[2] However if instructed to carefully focus the letters (as in Instruction 3), these subjects may then accommodate more accurately. Although this possibility limits the general applicability of my findings, a letter size several lines above acuity threshold (6/15 Snellen equivalent in this study) is representative of many everyday tasks.

All the subjects in this study were inexperienced, and a possibility with inexperienced subjects is to dispense with focusing instructions altogether and simply give instructions related to the task to be performed in the study. Experienced subjects would be better supplied with a focusing instruction due to the likelihood of biased focused strategies from participation in previous research.

Subject instructions should be considered carefully at the design stage of an experiment, and checked for possible ambiguities or nuances of meaning. Instructions should be delivered consistently to all subjects, preferably verbatim, and repeated at regular intervals to provide constant reinforcement. Even small differences in the wording of an instruction can lead to major differences in the outcome. Owens[21] and Adams and Johnson[22]

both investigated the Mandelbaum effect and found accommodation to be quite accurate for all their subjects when using the instruction 'relax and let your eye choose a target.' In contrast, the instruction used in this present study, 'look at the words but make no special effort to focus on them. Let your eyes relax and let them choose a focus,' led in general to response functions markedly different from those observed in the previous two studies. There are differences between the instructions. In the two studies of the Mandelbaum effect, the instruction to 'relax' was countered by the definite instruction to 'choose a target.' In this present study, choosing a 'focus' was an ambiguous instruction, and those subjects who were able used voluntary or other higher order control to relax their focus. It is also possible that subjects in this study interpreted 'make no special effort' simply as 'make no...effort'.

Methods of Target Presentation

Response functions for real space and Badal system targets are equivalent for practical purposes, and this suggests that it is valid to investigate static accommodation with a Badal system.

In the Badal system many of the monocular depth cues are absent. Despite the paucity of available depth cues, almost every subject was able to accurately accommodate in the Badal system (disregarding subjects who received Instruction 1). A number of suggestions can be made as to the strategies used by subjects to accommodate in the Badal system. Although some subjects may have used voluntary accommodation to 'hunt' for the target, not all subjects stated that they could voluntarily accommodate. Alternatively, as the subject approached the apparatus from a distance of about 50 cm, the 0.5 D Badal target was physically situated at a distance of approximately 2 D. Assuming the subject accommodated to the 2 D level, only a small amount of reflex accommodation was required to clear the target. From that point in time, targets were always moved in steps of 2 D or less, making it possible for reflex accommodation to clear the targets. Reflex responses to the targets would have depended on the low spatial frequency

components of the target to initially drive the response.[31,32] Another possibility is to use as a cue the small lateral shifts of the target or small changes in angular subtense with changes in stimulus level due to alignment errors of the Badal system.

Although the static accommodation response appears to be similar for both real space and Badal viewing, it is unlikely the same would be true for the dynamic accommodation response. For example, the addition of a changing size (looming) cue to the changing blur cue provided by the Badal system generally leads to more accurate responses with reduced phase lags.[33,34] Although real space viewing provides other depth cues besides looming, it is likely that dynamic responses would be more accurate in real space than for Badal system viewing.

Although objects normally increase in size as they move towards the eye, the real space targets in this study maintained constant angular size. This may have reduced the input to the spatiotopic system by removing the cue of familiar size. However other depth cues were still available, so it is difficult to estimate the potential magnitude of this effect. Also, dynamic size cues (looming) were available for a short time as the experimenter adjusted each target to its correct position. This cue was not consistent in duration or magnitude across conditions, and may have led to variability in the initial responses to the target.

Under Instruction 1, two subjects (subjects 6 and 21) demonstrated greater lags of accommodation for real space viewing than for Badal viewing. Because of counterbalancing, both subjects viewed the real space target after the Badal targets, and the observed differences may simply represent a practice effect; that is, the subjects were better able to use negative voluntary accommodation with practice.

In general most subjects can adequately accommodate to Badal targets, but some subjects are unable to perform this task adequately. The single pilot subject in this study was unable to relax accommodation to the 0.5 D target after first viewing targets at the higher stimulus levels (Figure 3.5). Although this subject received Instruction 1, 'make no special effort', it was

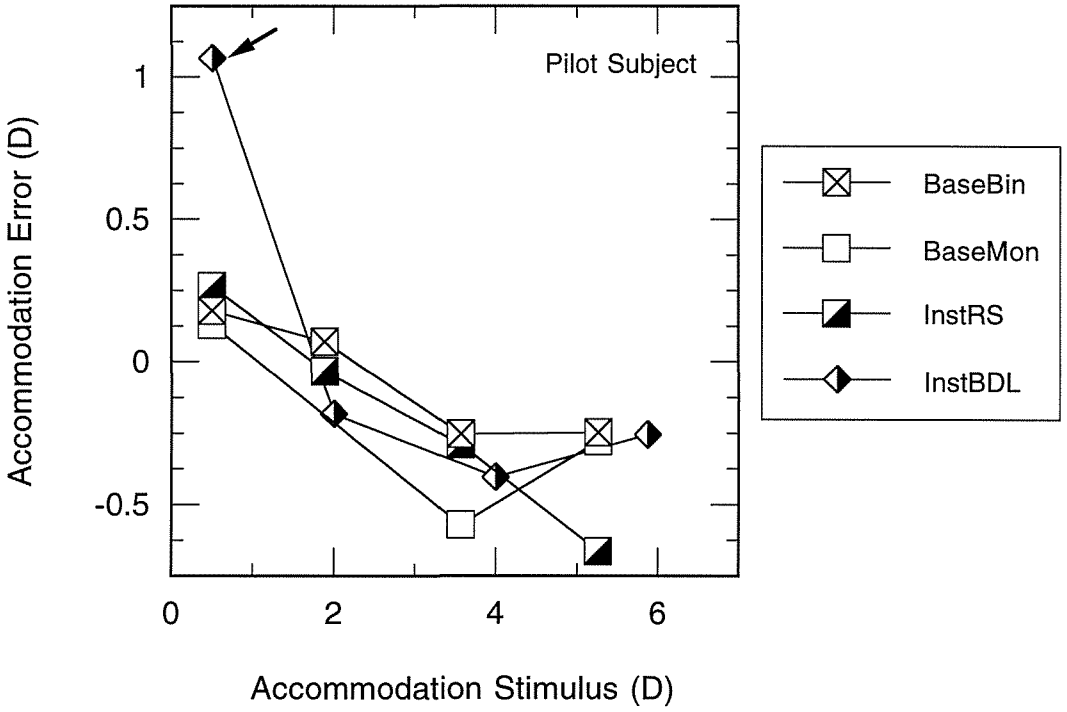


Figure 3.5. Mean accommodation responses of the pilot subject. The mean accommodation error is plotted as a function of the stimulus to accommodation. The arrow points to the subject's response when she was unable to relax focus while viewing the Badal target. Symbols as per Figure 3.2.

obvious from her comments that she was attempting to focus the target. The observed effects are unlikely to be an artefact of the instruction used at that particular time. When instructed to focus on the targets as clearly as possible, this subject in another Badal system demonstrated reduced gain to sinusoidally varying inputs and poor responses to step inputs.

As not all subjects have difficulty accommodating to Badal targets, this suggests some underlying individual cause. Heath noticed that some subjects show a 'reluctance' to relax accommodation from a near to a distant target.[35] Some persons may have poorly developed voluntary or reflex accommodation and may thus be disadvantaged in situations in which proximal cues are reduced or erroneous. These subjects may be more susceptible to the fixed angular size cue provided by the Badal target;[9] that is, because the retinal image of the Badal target does not change in size this may provide an erroneous cue to the subjects that the target is at a fixed

distance. An oculomotor condition or anomaly may inhibit correct accommodation in the Badal system. For example, some people show greater tonic adaptation than others.[36] Perhaps if such a subject viewed a target at a low stimulus level after pre-adapting at a higher stimulus level, the blurred detail of the target may not provide an adequate blur stimulus to accommodation. The person's accommodation in this situation would very slowly drift back towards the dark focus instead of responding to the target.

Subjects should be asked to report target blur whenever it occurs in an experimental session, and recordings should be checked as they are made for any unusual responses. Subjects may benefit from practice at the task and explanation of the Badal system.[14,15]

3.5. Summary

1. Subject instructions can have an influence on the accommodation stimulus–response function. Some instructions lead subjects to make voluntary changes in their focus or conscious changes in their attention to a target.
2. Responses with the instruction (no. 2) to 'view the target naturally' are not significantly different from responses with the instruction (no. 3) to 'focus carefully'. The responses with Instructions 2 and 3 only differ slightly from the baseline response obtained with an instruction to 'pick a word in the middle of the block of text and look at it.' Thus, responses with Instructions 2 and 3 are likely to be close to people's normal accommodation responses.
3. Responses with the instruction (no. 1) to 'make no special effort' are significantly different from those obtained with Instructions 2 and 3. Also, responses with Instruction 1 are significantly different from baseline responses. Instruction 1 leads many subjects to adopt a fairly fixed low accommodation level, and some subjects responses with Instruction 1 are highly variable. Instruction 1 leads many people to use voluntary accommodation to relax their focus. Some

subjects consciously try to relax their normal attention to the target, while others use 'true' voluntary accommodation to relax focus.

4. Steady accommodation responses are the same in real space and Badal viewing for most subjects, although some subjects have difficulty when trying to focus for a target in a Badal system.

References

1. Phillips, S.R. *Ocular Neurological Control Systems: Accommodation and the Near Response Triad.* PhD Thesis. Berkeley: University of California, 1974. pp. 74–122.
2. Charman, W.N. and J. Tucker. Dependence of accommodation response on the spatial frequency spectrum of the observed object. *Vision Res.* 1977, **17**, 129–139.
3. Owens, D.A. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980, **20**, 159–167.
4. Bour, L.J. The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Res.* 1981, **21**, 1287–1296.
5. Ciuffreda, K.J. and S.C. Hokoda. Spatial frequency dependence of accommodative responses in amblyopic eyes. *Vision Res.* 1983, **23**(12), 1585–1594.
6. Ciuffreda, K.J. and S.C. Hokoda. Effect of instruction and higher level control on the accommodative response spatial frequency profile. *Ophthalmic Physiol. Opt.* 1985, **5**(2), 221–223.
7. Badal, J. Optomètre métrique international du Dr Badal. Pour la mesure simultanée de la réfraction et de l'acuité visualle même chez les illettrés. *Ann. Ocul.* 1876, **75**(May/April), 101–117.
8. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 88–89.
9. Schor, C.M., J. Alexander, L. Cormack and S. Stevenson. Negative feedback control model of proximal convergence and accommodation. *Ophthalmic Physiol. Opt.* 1992, **12**, 307–318.
10. Ogle, K.N. *Researches in Binocular Vision.* 2nd printing. New York: Hafner, 1964. pp. 133–134.
11. Schober, H., H. Dehler and R. Kassel. Accommodation during observations with optical instruments. *J. Opt. Soc. Am.* 1970, **60**(1), 103–107.
12. Miege, C. and P. Denieul. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 165–171.
13. Allen, M.J. The stimulus to accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1955, **32**, 422–431.
14. Charman, W.N. and J. Tucker. Accommodation and color. *J. Opt. Soc. Am.* 1978, **68**(4), 459–471.
15. Randle, R.J. Responses of myopes to volitional control training of accommodation. *Ophthalmic Physiol. Opt.* 1988, **8**(3), 333–340.
16. McBrien, N.A. and M. Millodot. Clinical evaluation of the Canon Autoref R-1. *Am. J. Optom. Physiol. Opt.* 1985, **62**(11), 786–792.
17. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.

18. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin*. 1972, **77**(1), 54–64.
19. Malmstrom, F.V., R.J. Randle, J.S. Bendix and R.J. Weber. The visual accommodation response during concurrent mental activity. *Percept. Psychophys*. 1980, **28**(5), 440–448.
20. Keppel, G. *Design and Analysis. A Researcher's Handbook*. 2nd ed. Englewood Cliffs, N.J: Prentice-Hall, 1982. pp. 162–164; 377–378.
21. Owens, D.A. The Mandelbaum effect: Evidence for an accommodative bias toward intermediate viewing distances. *J. Opt. Soc. Am*. 1979, **69**(5), 646–652.
22. Adams, C.W. and C.A. Johnson. Steady-state and dynamic response properties of the Mandelbaum effect. *Vision Res*. 1991, **31**(4), 751–760.
23. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction*. Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
24. Ramsdale, C. Monocular and binocular accommodation. *Ophthalmic Opt*. 1979, **19**(14), 606–622.
25. McLin, L.M. and C.M. Schor. Voluntary effort as a stimulus to accommodation and vergence. *Invest. Ophthalmol. Visual Sci*. 1988, **29**(11), 1739–1746.
26. Jonides, J. Voluntary versus automatic control over the mind's eye's movement. *In:* J.B. Long and A.D. Baddeley eds. *Attention and Performance IX*. Hillsdale, N.J: Lawrence Erlbaum Associates, 1981. pp. 187–203.
27. Francis, E.L., J. Bai-Chuan, D.A. Owens, R.A. Tyrrell and H.W. Leibowitz. "Effort to see" affects vergence and accommodation but not their interactions [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl*. 1989, **30**(3), 135.
28. Ward, P.A. The effect of stimulus contrast on the accommodation response. *Ophthalmic Physiol. Opt*. 1987, **7**(1), 9–16.
29. Ward, P.A. and W.N. Charman. Effect of pupil size on steady state accommodation. *Vision Res*. 1985, **25**(9), 1317–1326.
30. Ciuffreda, K.J., S.C. Hokoda, G.K. Hung and J.L. Semmlow. Accommodative stimulus/response function in human amblyopia. *Doc. Ophthalmol*. 1984, **56**(4), 303–326.
31. Charman, W.N. and G. Heron. Spatial frequency and the dynamics of the accommodation response. *Opt. Acta (Lond.)*. 1979, **26**(2), 217–228.
32. Tucker, J. and W.N. Charman. Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. *Ophthalmic Physiol. Opt*. 1987, **7**(2), 137–142.
33. Kruger, P.B. and J. Pola. Changing target size is a stimulus for accommodation. *J. Opt. Soc. Am., A, Opt. Image Sci*. 1985, **2**(11), 1832–1835.
34. McLin, L.N., C.M. Schor and P.B. Kruger. Changing size (looming) as a stimulus to accommodation and vergence. *Vision Res*. 1988, **28**(8), 883–898.
35. Heath, G.G. The influence of visual acuity on accommodative responses of the eye. *Am. J. Optom. Arch. Am. Acad. Optom*. 1956, **33**(10), 513–524.
36. Schor, C. and D. Horner. Adaptive disorders of accommodation and vergence in binocular dysfunction. *Ophthalmic Physiol. Opt*. 1989, **9**(3), 264–268.

Chapter 4

Pupil Size and the Fluctuations of Accommodation

4.1. Introduction

The objective of this study is to determine how pupil size and mean accommodation response level affect the high and low frequency fluctuations of accommodation. Previous studies of the effect of pupil size on accommodation fluctuations yielded conflicting results,[1,2] and so one aim of this study is to see if the findings of either of these studies can be replicated using a different optometer and with a different experimental apparatus. Also, previous studies only used single, low accommodation stimulus levels. In this present study two accommodation stimulus levels are used to see how pupil size and mean accommodation response interact to affect the fluctuations of accommodation.

Pupil Size and Fluctuations of Accommodation

Campbell, Robson and Westheimer[1] were the first to demonstrate changes in the fluctuations of accommodation with pupil size. For a single subject, they continuously recorded the accommodation response to a steady target while the subject viewed with either a 7 mm or a 1 mm artificial pupil. A prominent peak at about 2 Hz was evident in the power spectra with the 7 mm pupil but disappeared with the 1 mm pupil. Also, the low frequency (< 0.5 Hz) spectral power increased with the small pupil. A number of factors which might have explained this finding can be ruled out. Retinal illuminance was not a factor because it was kept constant. Also, the optometer always recorded through the fully dilated pupil, and the mean accommodation response level was about 1 D in both cases. Campbell *et al.* stated that the disappearance of the 2 Hz peak with a small pupil indicated that the 2 Hz fluctuation was connected with the normal feedback loop of the accommodation control system. Unfortunately, power spectra calculations were laborious at the time, and so only the results of two runs on one subject were presented.

At about the same time, Stark, Takahashi and Zames investigated the dynamic accommodation responses of subject 'J.R.' who had previously participated in the study of Campbell *et al.*[1,3] Stark *et al.* found that the 2 Hz accommodation fluctuations in this subject corresponded with a 2 Hz borderline instability in the dynamic accommodation response to small amplitude sinusoidal target motion.[3] Thus, Stark *et al.* concluded that the 2 Hz fluctuations of accommodation are nothing more than a borderline instability of the accommodation control system. Furthermore, their control model could explain both the reduction in 2 Hz fluctuations and the increase in low frequency fluctuations when viewing through a small pupil, as originally found by Campbell *et al.*[1] Campbell could explain the increase in low frequency fluctuations for small pupils using a Nyquist diagram, but he could not explain the decrease in the 2 Hz fluctuations.[4]

Recently a number of studies using the Canon Autoref optometer have demonstrated that a high frequency oscillation in the 0.9–2.5 Hz range is almost perfectly correlated with the ocular pulse.[5,6] These studies seem to contradict the idea that there is a fixed 2 Hz fluctuation resulting from accommodation system instability. Furthermore, these studies raise the question of why a high frequency fluctuation caused by the ocular pulse would vary so greatly with stimulus conditions (i.e. pupil size) as originally found by Campbell *et al.*[1]

Gray *et al.* investigated the effect of pupil size on accommodation fluctuations and found, in contradiction to Campbell *et al.*, that the high frequency fluctuations of accommodation do not change with pupil size.[1,2] However the low frequency fluctuations were larger for pupils smaller than about 2 mm. The findings of Gray *et al.* support the idea that the high frequency fluctuations are not under active neural control as an aid to accommodation control. If the high frequency fluctuations were under active neural control then it would be expected that they would increase to make up for the larger depth of focus when viewing through a small pupil.[7,8]

Mean Accommodation Level and Fluctuations of Accommodation

The r.m.s. value of the accommodation fluctuations and the high frequency fluctuations increase in amplitude for higher mean accommodation response levels.[9,10] Miege and Denieul found for two subjects that the amplitudes of both the total fluctuations and the high frequency fluctuations of accommodation are minimal at the far and near points, and maximal at the middle of the accommodation range (see section 1.2.2.3).[10] However, previous studies on the effect of pupil size on fluctuations of accommodation have presented targets to their subjects at low stimulus levels.[1,2] It may be that the effects of pupil size on fluctuations are more easily detected at higher mean response levels where the fluctuations have a greater magnitude.

As the low frequency fluctuations have been hypothesised to aid the accommodation response to steady targets,[8,11] it may be more valuable to investigate these fluctuations when accommodation is operating for a near task rather than a more distant task as in previous studies.

Interactions between Pupil Size and Mean Accommodation Level

In this study accommodation was recorded for a number of different pupil sizes and target stimulus levels. In this way it was possible to investigate the interactions between pupil size, mean accommodation level and fluctuations of accommodation. For example, if a person views a near target through a small artificial pupil, the large depth of focus afforded by the pupil allows them to adopt a lower, more inaccurate accommodation response.[11,12] On the basis of the small pupil alone we may expect an increase in low frequency fluctuation,[2] but on the basis of the lower mean response level alone we may expect a decrease in low frequency fluctuation.[10] The actual change in fluctuations may in fact depend on both pupil size and mean response level.

4.2. Methods

Subjects

Four subjects participated in the study. All were highly experienced in accommodation studies and were familiar with the Badal viewing system. Their characteristics are listed in Table 4.1.

Apparatus

The dynamic accommodation response was recorded with a modified Bausch & Lomb Safir Ophthalmetron infra-red optometer modified to continuously record accommodation along the vertical meridian of the subject's right eye (see Appendix B). Targets were presented in Maxwellian view in the accompanying Badal target system to the subject's right eye (see Appendix B). Artificial pupils of 1 mm, 2 mm, 4 mm, and 6 mm could be

Table 4.1. Subject Characteristics

	Subject			
	A	*B*	*C*	*D*
Age (years)	21	25	39	27
R.E. Amp. of Accomm.	7.0	7.25	3.5	5.4
R.E. Subjective Refraction*	+0.1/-0.25 × 25†	+0.1 DS	-1.9 DS	+1.1 DS
R.E. Visual Acuity	$6/3^{-1}$	6/4.5	6/4.8	$6/3.8^{-1}$

* Subjective refractions are referred to an arbitrary entrance pupil 3.05 mm behind the corneal vertex. † Subject A's astigmatism was not corrected.

placed at an artificial pupil plane in the Badal system. These pupils were imaged as if at the eye's pupil, however the Ophthalmetron could record through the real eye's fully dilated pupil. Subjects were stabilised with a dental bite board and head rest.

Target

The target was a high contrast black on white Maltese Cross with two superimposed concentric rings. The cross was 4° wide. The limbs of the cross had a limb width of 50 seconds arc at the centre which increased to 20.5 minutes arc at the edges. The rings had inner diameters of 0.9° and 2.2° respectively, and limb widths of 2.45 minute arc and 4.7 minute arc respectively.

Procedure

PROTOCOLS FOR THE USE OF OPHTHALMIC DRUGS

Before starting the experiment, I used routine procedures to ensure that the various topical ocular drugs could be used safely with each subject. The drugs used at various times (in this and other studies reported in this work) were cyclopentolate (0.5%, 1.0%), tropicamide (0.5%, 1.0%), phenylephrine (2.5%) and benoxinate (0.4%). For the mydriatic drugs (cyclopentolate, tropicamide and phenylephrine), subjects were only included if they met the following criteria: intra-ocular pressure less than 17 mm Hg in both eyes, no

history of glaucoma; no glaucomatous signs by ophthalmoscopy; wide anterior chamber angles (van Herrick ratio of 1:2 or wider); no history of adverse reactions to the particular drug being used. In addition subjects were to have no history of epilepsy if cyclopentolate was to be used. In addition, if phenylephrine was to be used then the subject needed to fill the following criteria: no history of hypertension, hypotension, cardiac disease, angina, heart attack, arteriosclerosis, aneurisms, cerebrovascular accident, diabetes, hyperthyroidism or asthma; no use within the previous month of tricyclic anti-depressants, MAO inhibitors, α or β adrenergic blockers, reserpine, guanethidine, methyldopa, or anticholinergics; systolic and diastolic blood pressures of less than 140 and 90 mm Hg respectively; older than 10 years of age; no corneal epithelial injury. If benoxinate was to be used then the subject had to have no corneal epithelial injury and no history of abnormal reactions to anaesthetics.

PRELIMINARY SESSION

I performed individual calibrations of Ophthalmetron voltage output to subjective refraction for each subject while their right eye was cyclopleged with cyclopentolate (see section B.5). This was necessary to convert Ophthalmetron voltage output to accommodation readings.

EXPERIMENTAL SESSION

One drop of 0.4% benoxinate was instilled in the subject's right eye, followed a minute or two later with 1 drop of 2.5% phenylephrine. Mydriasis was required to prevent spurious readings from the Ophthalmetron, and also to ensure that the real eye pupil was larger than the largest artificial pupil size of 6 mm. Phenylephrine is known to influence accommodation, and its effects in this study need to be considered.

Phenylephrine in higher doses (2 drops of 10% solution) leads to a reduction in both the accommodation stimulus–response slope and the amplitude of accommodation, and also increases the response times to step stimuli.[13] The subjective amplitude of accommodation is also reduced with

2.5% phenylephrine, and this effect is amplified with prior instillation of a topical anaesthetic.[14] Tonic accommodation is unlikely to be affected by phenylephrine.[15] Phenylephrine has the potential to cause vasoconstriction of the ciliary body vessels via α adrenergic receptors,[16] and also leads to increased blood pressure and reduced heart rate in some subjects.[17] These changes could affect the fluctuations of accommodation. Heron *et al.*[18] found a decrease in the low frequency (<1 Hz) power spectrum density values with an unstated dose of 2.5% Phenylephrine in a single subject, but it is uncertain from the description of their procedures whether the experimental design took into account time order effects. In summary, the phenylephrine dose used in this study may have affected the steady state response and fluctuations of accommodation by a small amount. However, comparisons between various conditions should still be valid. A small dose (1 drop of 2.5% solution) was used to reduce the potential effects of phenylephrine on the fluctuations of accommodation.

When the subject's pupil had sufficiently dilated, I measured the subjective amplitude of accommodation with a Rodenstock Hand Optometer (Rodenstock, Munich). A 5 mm pupil was put in place to control depth of focus effects.

Artificial pupil sizes of 1 mm, 2 mm, 4 mm, and 6 mm, and stimulus levels of approximately 1.5 D and 3 D were used in this study. The order of presentation of the various pupil sizes were counterbalanced across subjects.[19] The experimental session was divided into two blocks — all the presentations at 1.5 D were presented in one block, and all presentations at 3 D in the other block. The order of presentation of the nominally 1.5 D and 3 D stimulus levels was counterbalanced across subjects.[19]

Because the target was presented in the Badal system, its angular size and luminance did not change with accommodation stimulus level. Target luminance was approximately 40 $cd.m^{-2}$ for the 4 mm and 6 mm pupils, which is sufficient for an accurate accommodation response.[20] However the light source of the system was not a true point source, and it was found that the 1 mm and 2 mm artificial pupils intersected the aerial image of the light

source, and thus decreased the retinal illuminance of the target (see control experiment below).

The subject's task was to view the steady Maltese cross target in the Badal target system with their right eye, and with the left eye patched. The subject was given the following instruction:

> Look at the centre of the Maltese cross. View it naturally, the same as when viewing a book or a sign at the same distance.

Five recordings of accommodation were made for each pupil size – stimulus level combination. The response was sampled at 35.97 Hz for 14.2 seconds to give a total of 512 data points. This frequency is much higher than the Nyquist frequency of the highest frequencies likely to occur in the accommodation record. This particular frequency was chosen because runs on a model eye revealed no spurious peaks in the 0 - 6 Hz region attributable to aliasing with the electrical mains frequency (see section B.7). Records were saved to disc for later analysis.

At the conclusion of the experiment, the right eye pupil size was estimated with the bright illumination of the Ophthalmetron's inbuilt alignment system, and a pentorch held to the lateral side of the eye. The actual pupils in this bright illumination ranged between 7 mm and 8 mm, and thus were larger than the largest artificial pupil of 6 mm.

Analysis

Sampled voltage outputs from the Ophthalmetron were converted to accommodation values using the individual calibration equations previously obtained (See Appendix E). Power spectrum analysis was performed using an application written by Brett Davis. During the experiment, subjects were allowed to blink when necessary, and these appeared as sharp discontinuities in the accommodation records. They were edited prior to Fourier analysis using an algorithm previously described.[a] The boundaries of the blink affected data were selected by eye. The algorithm then removed

the intervening data, and selected 15 data points on either side of the deleted data. It then interpolated over the range of the delated data using a cubic polynomial fit. In no case did this interpolated data exceed more than 4.5% of the total record — a value smaller than the 5% criterion adopted by other workers.[21]

The algorithm then removed the mean level (d.c. level) of each accommodation record. It is important to remove the d.c. level because otherwise it 'spills over' from the 0 Hz frequency bin of the power spectrum into adjacent low frequency bins and appears as spurious low frequency fluctuations. A Hamming window was applied to the data, and it has the form

$$W(k) = 0.54 + 0.46\cos\frac{\pi(2k - N + 1)}{N + 1}, \qquad (4.1)$$

where $k = 0, 1, 2, \ldots N - 1$. The kth data point in the accommodation record is multiplied by $W(k)$, and there are N data points in the record. The data was Fourier filtered at 10 Hz.

The *effective deviation* was calculated over two frequency ranges for each individual power spectrum. I define the *effective deviation* as the square root of the area under the power spectrum density curve between two frequencies, multiplied by $(\pi/2)$. Its unit is dioptres, and it is conceptually analogous with the standard deviation of the raw accommodation response, except that the effective deviation represents the variability within a certain frequency range whereas the standard deviation represents variability over all temporal frequencies. The standard deviation of a record is equivalent to the effective deviation if the effective deviation is obtained over the entire frequency range of the power spectrum curve.* The advantage of the effective deviation parameter is that it has direct physical meaning.

The effective deviation was calculated over two frequency ranges:

1. Low frequency range (0–0.632 Hz);
2. High frequency range (0.703–2.529 Hz).

* This relationship between the standard deviation and the effective deviation was established empirically for the particular power spectrum algorithm used in this study. As power spectrum algorithms differ, this relationship may also differ between algorithms.

The equations used to calculate these parameters are

$$e.d._{low} = \frac{\pi}{2} \cdot \sqrt{\sum_{f=0}^{0.632} S_f} \ , \tag{4.2}$$

$$e.d._{high} = \frac{\pi}{2} \cdot \sqrt{\sum_{f=0.703}^{2.529} S_f} \ , \tag{4.3}$$

where $e.d._{low}$ is the low frequency effective deviation, $e.d._{high}$ is the high frequency effective deviation, and S_f is the power spectrum density ($D^2.Hz^{-1}$) in the bin having a frequency of f.

Unlike Gray *et al.*, the power spectra in this study did not show any *single* or *consistent* high frequency peaks, and so the spectral power was integrated over a wide frequency range. (This point is discussed later.) These frequency ranges, although arbitrary, were based on previous studies which have found high frequency peaks in the range 0.9–2.5 Hz (section 1.2.2.1). The value of 0.703 Hz for the lower boundary of the high frequency range encompasses the above values and also allows for subjects with pulse rates down to 42 beats.min^{-1}. (The high frequency peak has been found to correlate with the pulse rate.[5]) Gray *et al.* determined average power spectrum density in a 0.6 Hz range centred on the high frequency peak.[2]

For each condition the mean power spectrum was obtained by averaging 5 individual power spectra. For each run the mean accommodation level was also calculated after spurious data due to blinks had been deleted.

Control Experiments

CYCLOPLEGED AND MODEL EYES

One researcher who had previously used the Q.U.T. Ophthalmetron optometer had generally been unable to locate *prominent* high frequency power spectrum peaks. It was considered possible that the Ophthalmetron was not sufficiently sensitive to detect these high frequency fluctuations of accommodation. To test this hypothesis, accommodation data were obtained on two eyes that had been cyclopleged. It was thought this would reduce the overall noise in the response and better allow any high frequency peaks in

the power spectrum to be observed. Data was also collected from a Bausch & Lomb model eye (provided with the Ophthalmetron).

Accommodation was recorded in two cyclopleged eyes (right eyes of subjects C & D), using sampling procedures similar to that already described. One drop of 1.0% cyclopentolate was instilled in the right eye, and subjective amplitudes of accommodation were 0.50 D at the time of testing. The cross target was placed at the subject's far point, and was viewed with a 4 mm artificial pupil in place at the artificial pupil plane of the Badal target system. Five useable runs were obtained for subject 3 and nine runs were obtained for subject 4. Power spectra were derived as previously described.

ILLUMINANCE EFFECTS

Target luminance was approximately 40 cd.m^{-2} for the 4 mm and 6 mm pupils (section B.4). However the light source of the system was not a true point source, and it was found that the 1 mm and 2 mm artificial pupils intersected the aerial image of the light source, and thus decreased the retinal illuminance of the target. The estimated 'equivalent luminances' for the 1 mm and 2 mm pupils were 6 cd.m^{-2} and 22 cd.m^{-2} respectively. The 'equivalent luminance' is given by ($40\,\text{cd.m}^{-2} \times A_{pupil}/A_{light}$), where 40 cd.m^{-2} is the estimated luminance of the target, A_{pupil} is the area of the light source aerial image passed by the pupil, and A_{light} is the area of the light source aerial image. The purpose of this control experiment was to determine the effect of the changes in retinal illuminance on accommodation fluctuations.

The experimental protocol was very similar to that of the main study. Subject D from the main experiment served as a subject. The Maltese cross target was viewed at two stimulus levels (1.69 D & 3.18 D), through two pupil sizes (1 mm & 6 mm), and at two 'equivalent luminances' (6 cd.m^{-2} & 40 cd.m^{-2}). The different luminances were approximately obtained with neutral density filters placed in the light path of the Badal target system.

The order of presentation of the various stimulus level – pupil size – target luminance combinations was counterbalanced.[19] For each condition,

ten records of accommodation were taken, sampling at 35.97 Hz for 14.2 seconds. The radial pulse rate was measured throughout the session.

Accommodation records were analysed as in the main experiment, and the mean power spectrum for each condition was obtained by averaging ten individual power spectra. Partial correlations were used to determine the effect of target luminance on the fluctuations of accommodation.

4.3. Results

Before performing formal statistical tests, the *effective deviation* data were plotted as a function of mean accommodation response level (Figures 4.1–4.4) and as a function of pupil size (Figure 4.5).

The low frequency fluctuations appear to be larger at higher accommodation response levels for subjects A and D (Figures 4.1 & 4.4), but not for subjects B and C (Figures 4.2 & 4.3). It is difficult to say by visual inspection whether the high frequency fluctuations depend on the accommodation response level.

In all subjects, the low frequency fluctuations appear to be larger for small pupils, while the high frequency fluctuations appear to be independent of pupil size (Figure 4.5). It is interesting to note that, when viewing a near target, the low frequency fluctuations are maximal for a 2 mm pupil but then decrease for a smaller 1 mm pupil. This effect is obvious for subjects A and B, but not so obvious for subjects C and D.

To test the previously described observations, partial correlations were calculated between a number of variables (Table 4.2). A partial correlation is the correlation between a first and second variable while the effects of one or more other variables are mathematically held constant (see section C.1, or Pedhazur for a general discussion[22]). For example a partial correlation can be calculated which represents the correlation between pupil size and low frequency effective deviation, but with the effects of mean accommodation level held constant.

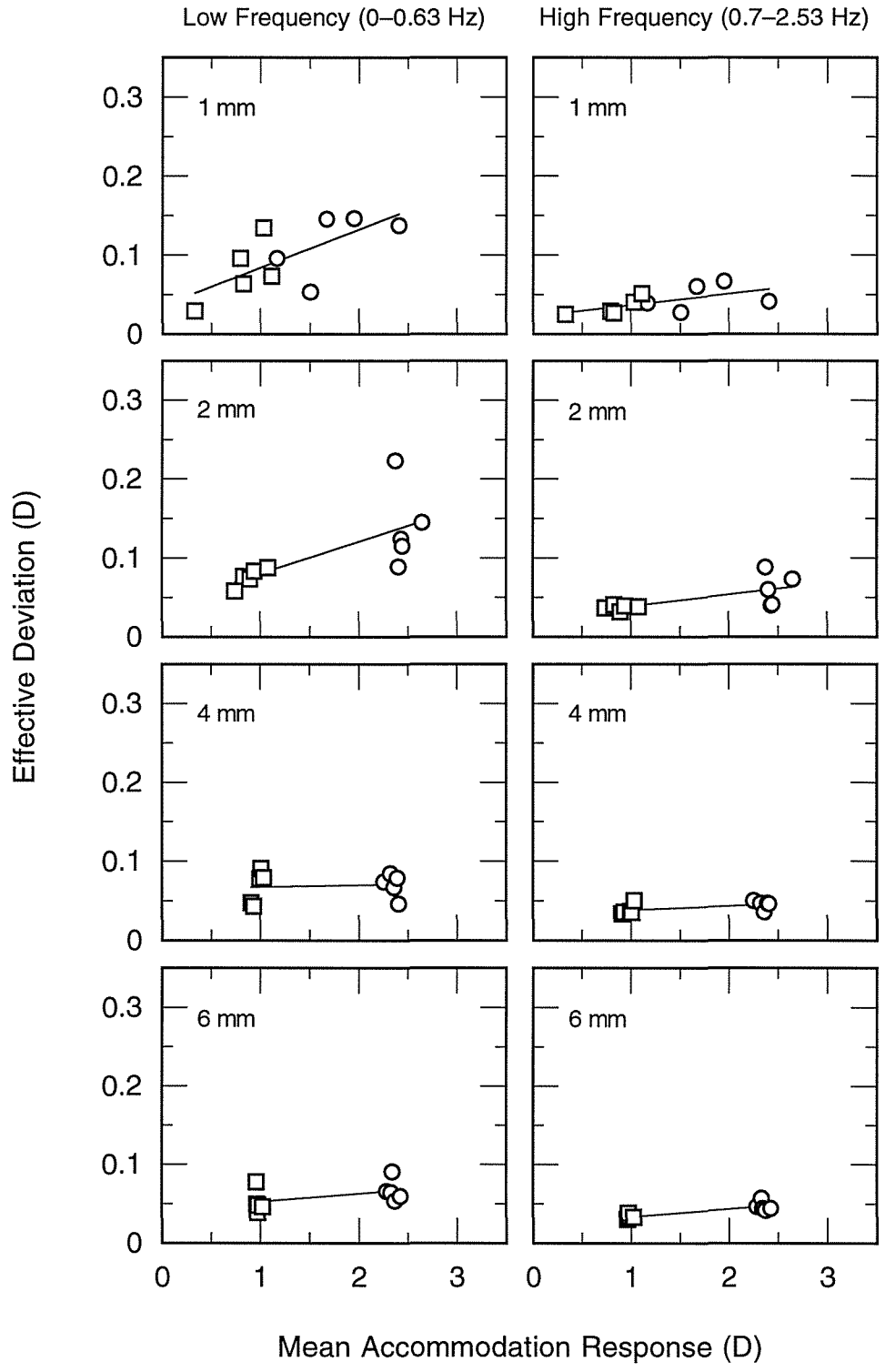


Figure 4.1. Low and high frequency fluctuations of accommodation as a function of mean accommodation response level and pupil size for subject A. The effective deviation is a measure of accommodation fluctuations (equations 4.2, 4.3). Stimulus levels were 1.6 D (squares), and 3.1 D (circles). Best fit lines calculated by principal axis regression are also shown.

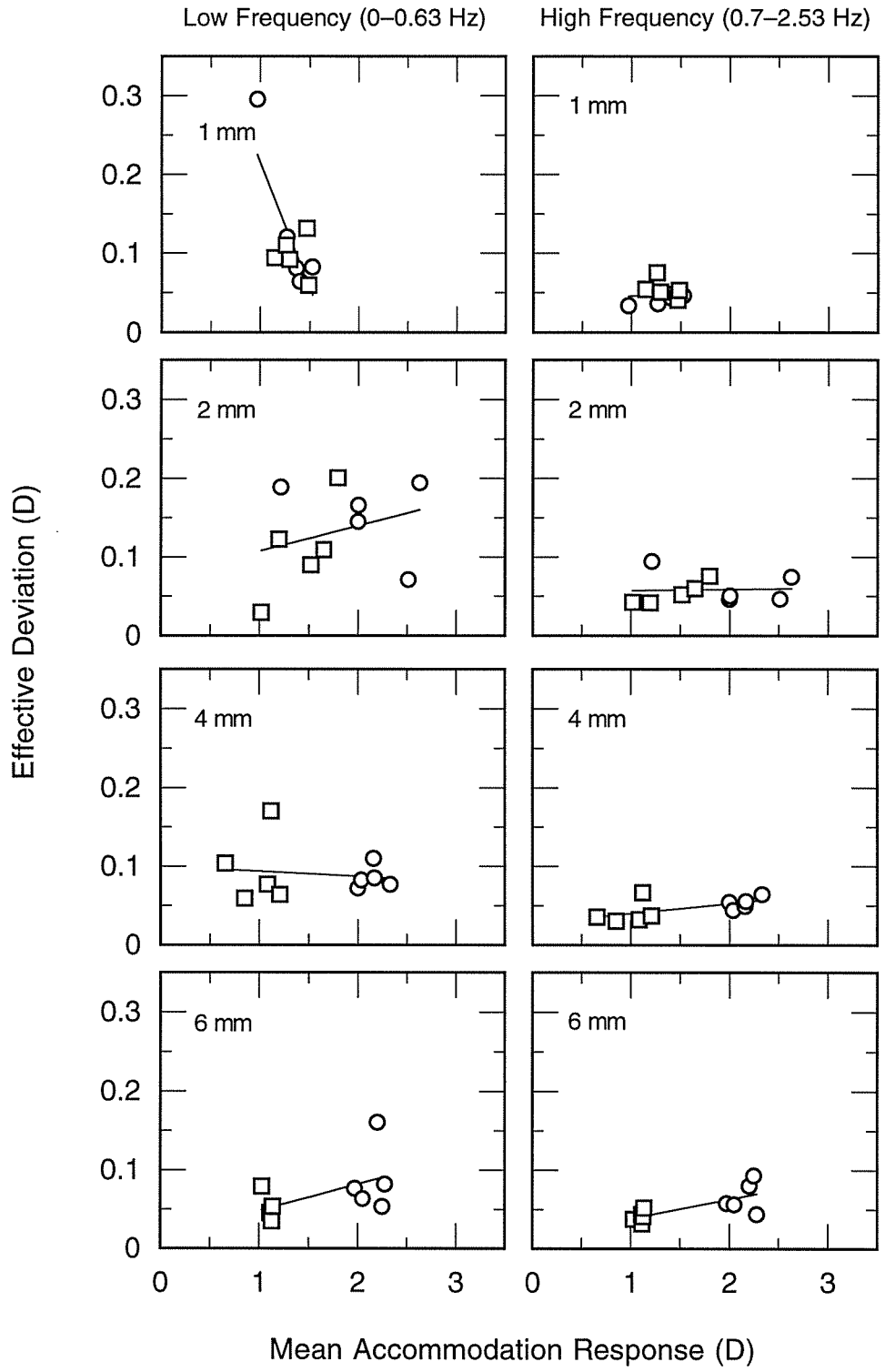


Figure 4.2. Low and high frequency fluctuations of accommodation as a function of mean accommodation response level and pupil size for subject B. Other details are as for Figure 4.1.

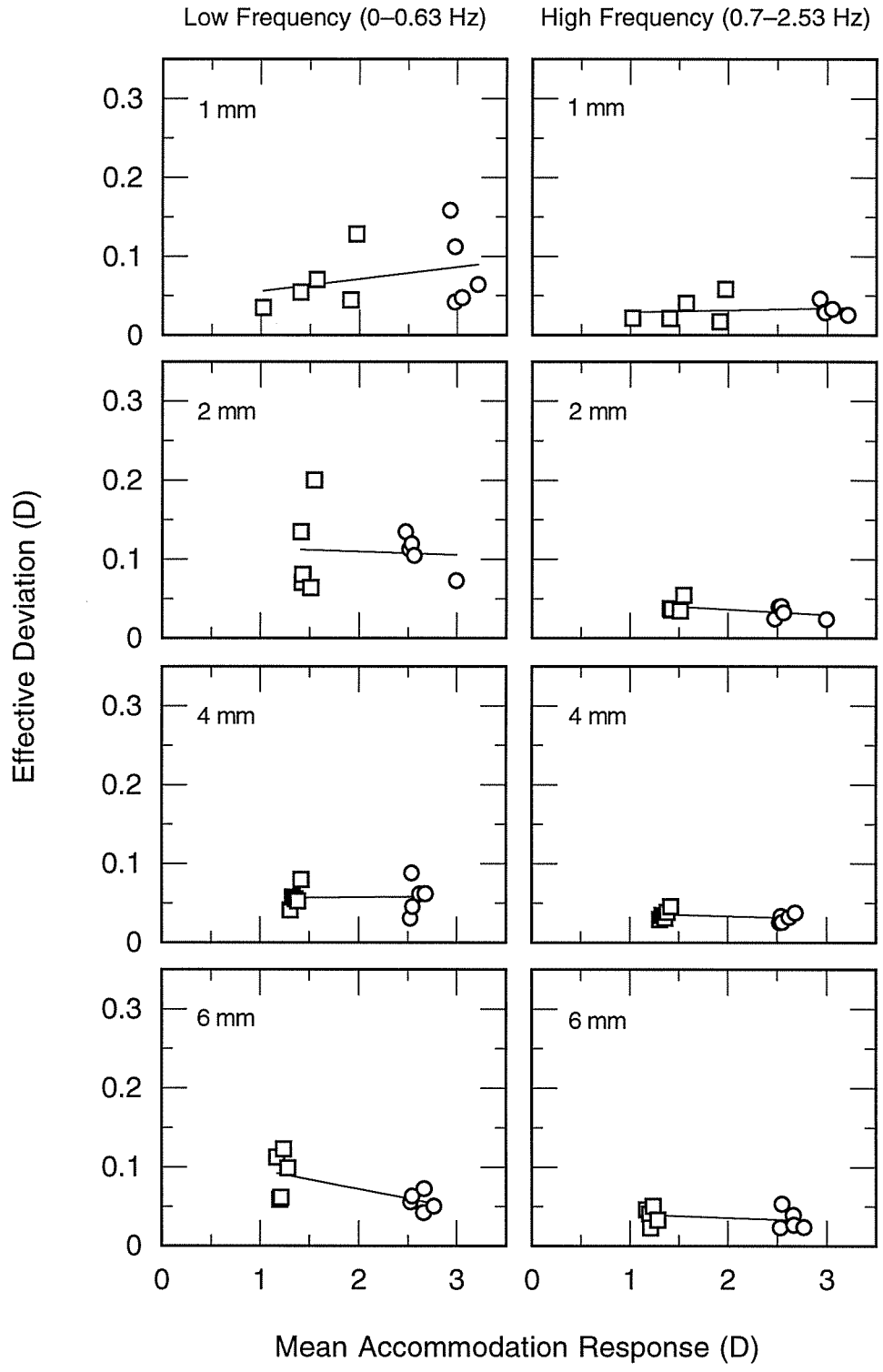


Figure 4.3. Low and high frequency fluctuations of accommodation as a function of mean accommodation response level and pupil size for subject C. Other details are as for Figure 4.1.

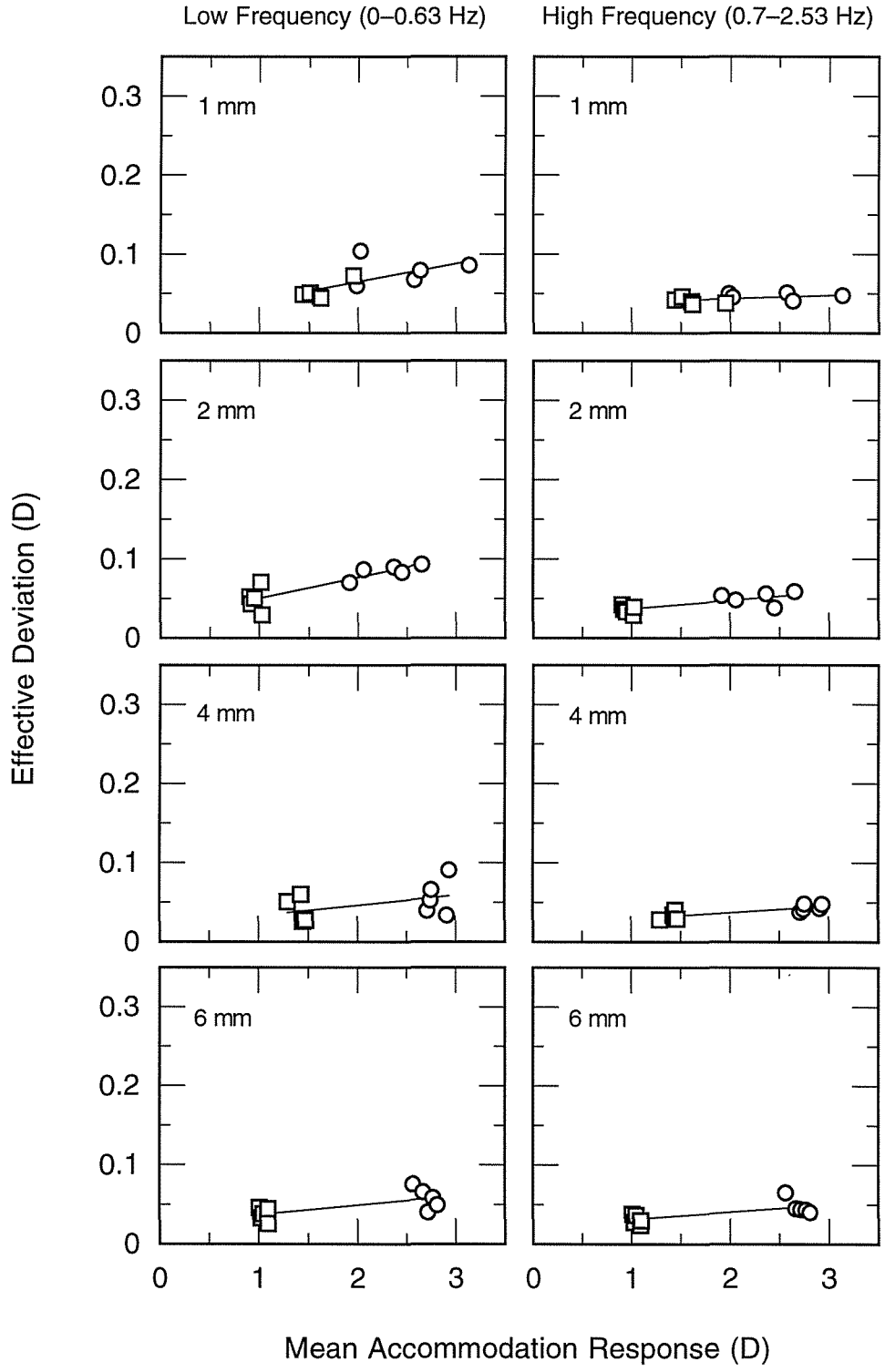


Figure 4.4. Low and high frequency fluctuations of accommodation as a function of mean accommodation response level and pupil size for subject D. Other details as for Figure 4.1, except that the stimulus levels were 1.7 D (squares) and 3.2 D (circles).

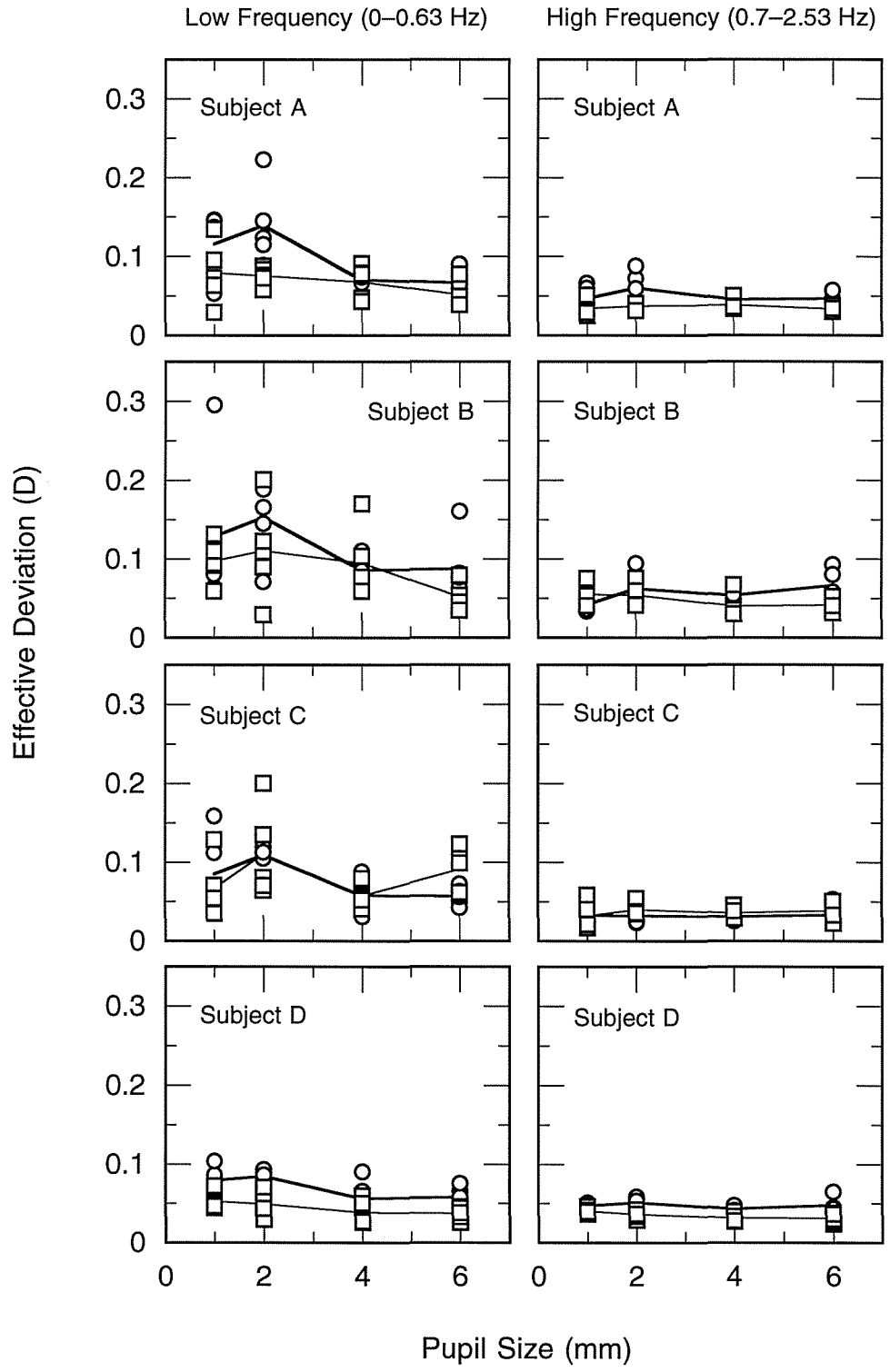


Figure 4.5. Low and high frequency fluctuations of accommodation as a function of pupil size for subjects A, B, C & D. The effective deviation is a measure of accommodation fluctuations (equations 4.2, 4.3). Stimulus levels were 1.6 D or 1.7 D (subject D) (squares), and 3.1 or 3.2 D (subject D) (circles). Thin lines and bold lines connect the mean data for low and high stimulus levels respectively.

Table 4.2. Partial correlations demonstrating the influence of pupil size and mean accommodation level on high and low frequency fluctuations of accommodation.

Variables			*Partial Correlations† and Probabilities* ($r_{12.3}, p$)				*Prop'n S's showing sign. corr'n*
1	*2*	*3*	*Subject A*	*Subject B*	*Subject C*	*Subject D*	
AR	e.d. low	Pupil	+0.53	+0.14	-0.07	+0.56	2/4
			<0.001**	0.40	0.67	<0.001**	
	e.d. high	Pupil	+0.63	+0.45	-0.18	+0.63	3/4
			<0.001**	0.004*	0.28	<0.001**	
Pupil	e.d. low	AR	-0.59	-0.40	-0.22	-0.49	3/4
			<0.001**	0.01*	0.18	0.002**	
	e.d. high	AR	-0.25	-0.04	0.06	-0.31	0/4
			0.13	0.82	0.73	0.06	

† Read $r_{12.3}$ as the partial correlation between variable 1 and variable 2 with the effects of variable 3 held constant. See section C.1 for information on partial correlations. *AR* is the mean accommodation response level (D), *Pupil* is the pupil size (mm), *e.d. low* is the low frequency effective deviation (see equation 4.2), *e.d. high* is the high frequency effective deviation (see equation 4.3). Correlations significant at the 5% level are denoted by an asterisk, and correlations significant at the more stringent Bonferroni corrected level (0.003) are denoted by a double asterisk.

Partial correlations show that low frequency fluctuations increase at higher mean accommodation response levels for half of the subjects (Table 4.2). For three of the subjects, high frequency fluctuations increase with higher mean accommodation response levels. These results agree with previous studies.[9,10,23]

Low frequency fluctuations increase with smaller pupils for three subjects, but no subjects show any significant change in high frequency fluctuations with pupil size (Table 4.2). This finding agrees with the study of Gray *et al.*[2]

When viewing a near target, subjects seem to show maximal low frequency fluctuations with a 2 mm pupil, but smaller low frequency fluctuations with a 1 mm pupil (Figure 4.5). This difference between the

1 mm and 2 mm pupils was not statistically significant (at the 5% level) for any subject, using partial correlations with the effects of mean accommodation level held constant. (The partial correlation coefficient values were -0.07, 0.45, -0.27, and 0.26 for subject A, B, C and D respectively.)

It was mentioned in the Methods section that the power spectra in this study generally did not show any single or consistent high frequency peaks, necessitating a parameter (effective deviation) that integrated over a wide range of high frequencies. Mean power spectra for subjects A, B, and D show multiple high frequency peaks which may be due to the small number of samples (n = 5) used to calculate each mean spectrum. Mean power spectra for subject C show no obvious high frequency peak (Figures 4.6–4.9).

Control Experiments

CYCLOPLEGED AND MODEL EYES

Under cycloplegia, a medium frequency peak at 0.73 Hz was noted for subject C, and a high frequency peak at 1.1 Hz for subject D (Figure 4.10). An estimate was made of the physical peak to peak amplitude of the accommodation fluctuations at this frequency. If the effective deviation is calculated over a *small* frequency range then it is possible to convert this 'standard deviation' of a sine wave into the peak-to-peak amplitude of a sine wave using the equation

$$\overline{A}_p = 2\sqrt{2}.(e.d.)\ , \qquad (4.4)$$

where $\overline{A}_p$ is the mean peak-to-peak amplitude of a sine wave at the frequency of interest, and *e.d.* is the effective deviation at the frequency of interest.

Using equation (4.4), the 0.73 Hz fluctuation in the cyclopleged eye of subject C has a mean peak-to-peak amplitude of 0.02 D, and for subject D, the fluctuation at 1.1 Hz has a mean peak-to-peak amplitude of 0.05 D. These values are extremely small, and approach the analog to digital resolution of the system of approximately 0.01 D. The presence of these obvious peaks shows that the Ophthalmetron optometer used in this study should have

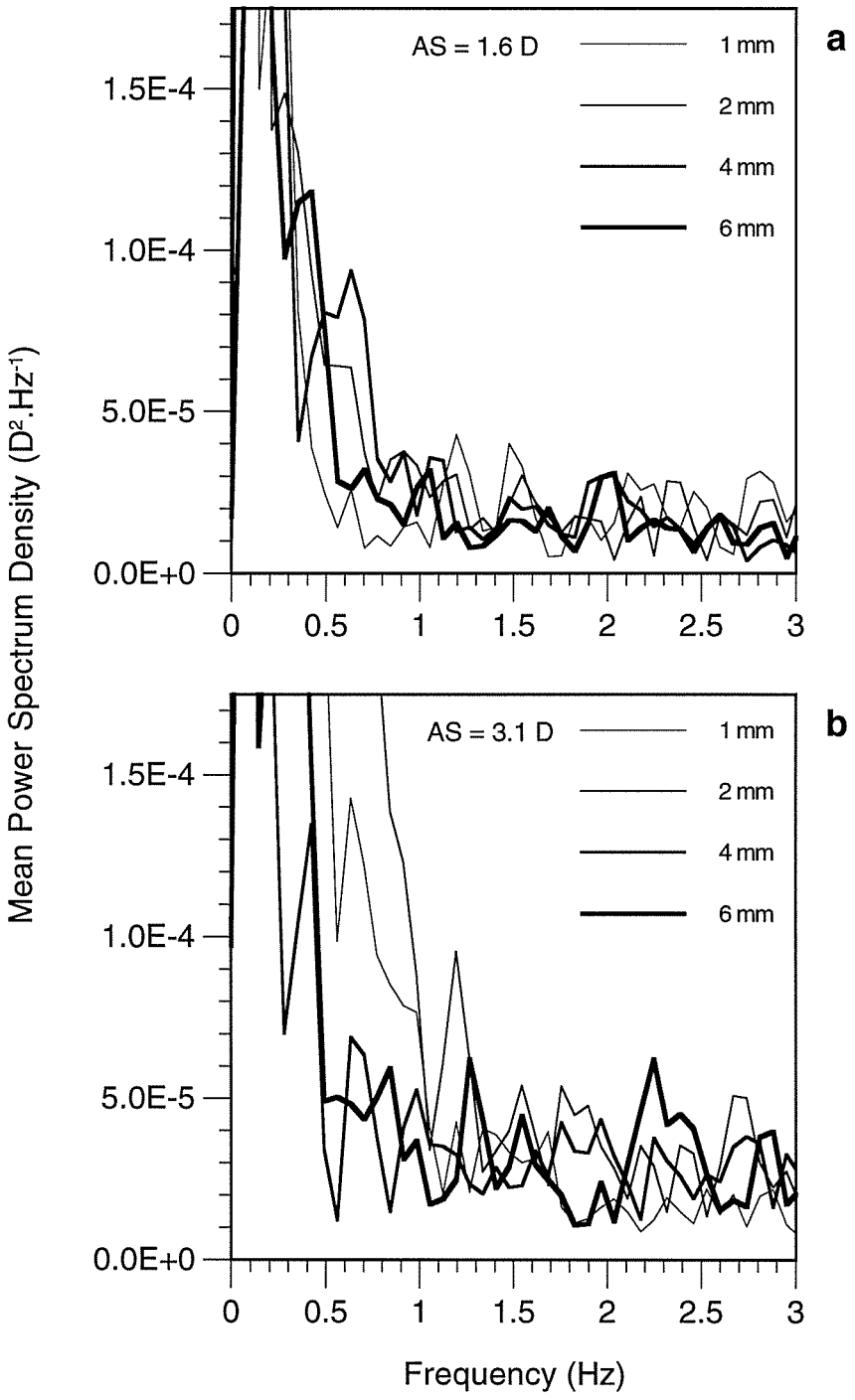


Figure 4.6. Mean power spectra for subject A with the target stimulus level set at (**a**) 1.6 D, or (**b**) 3.1 D. Each curve is the mean of 5 individual power spectra. Pupil sizes are shown.

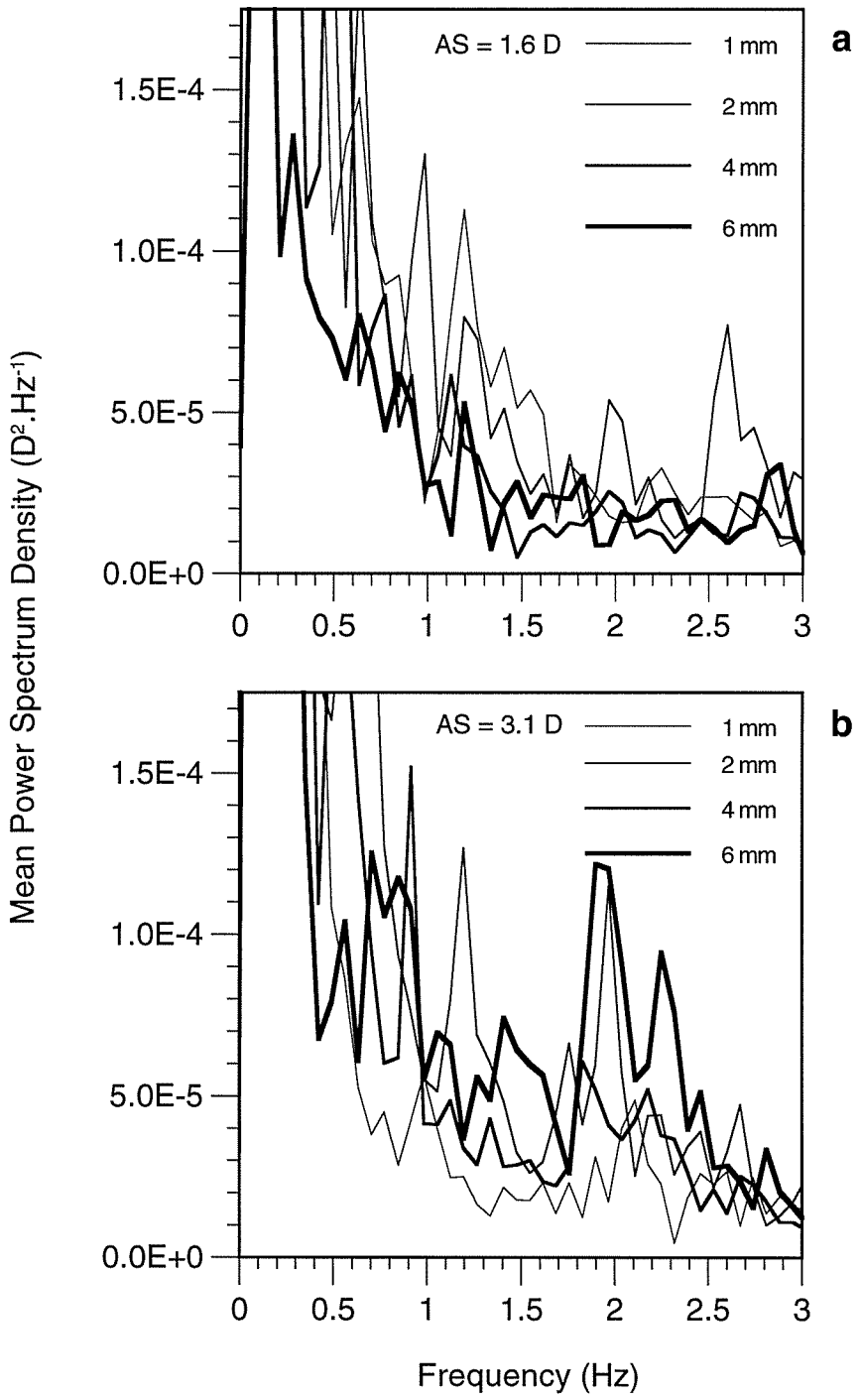


Figure 4.7. Mean power spectra for subject B with the target stimulus level set at (**a**) 1.6 D, or (**b**) 3.1 D. Each curve is the mean of 5 individual power spectra. Pupil sizes are shown.

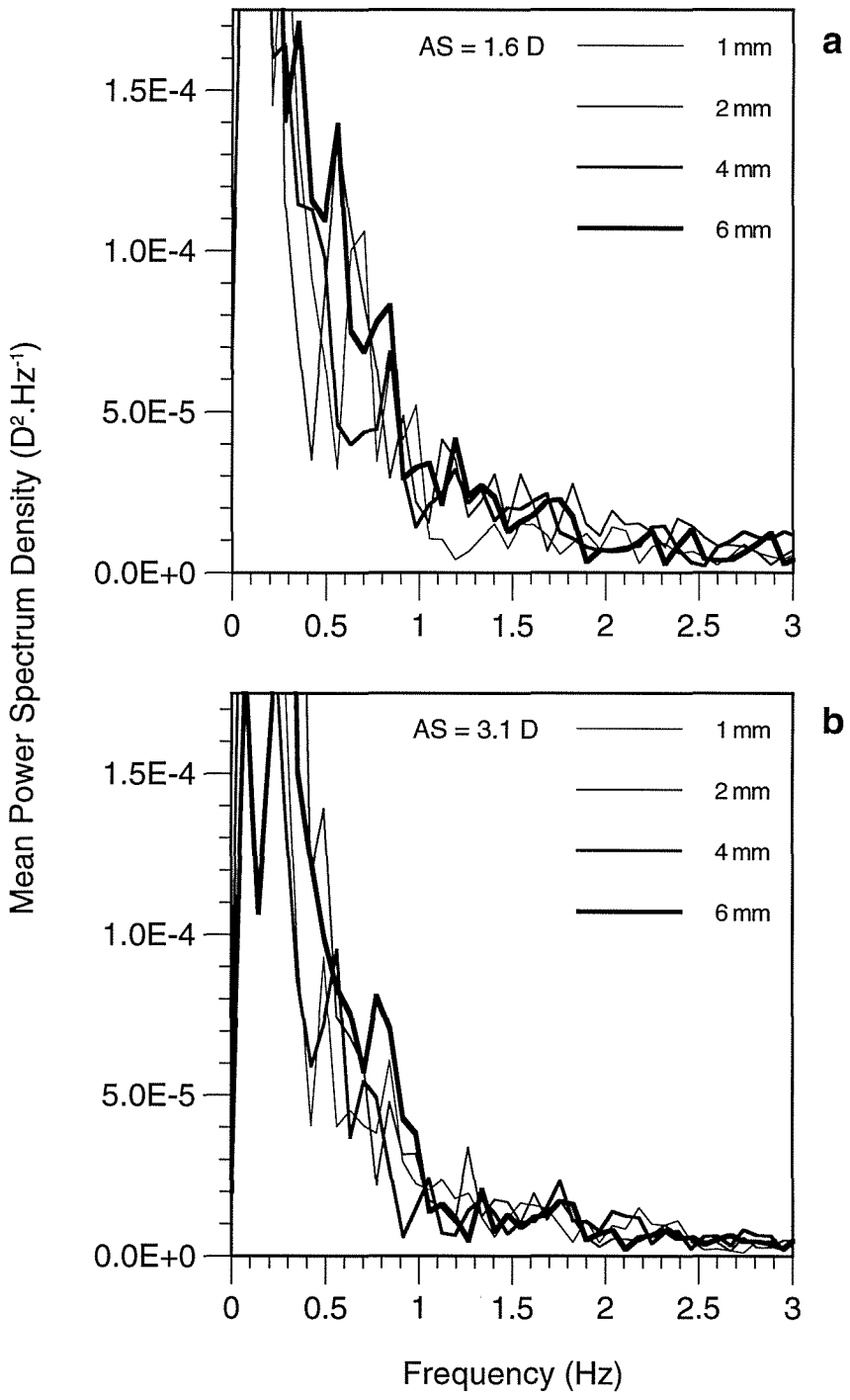


Figure 4.8. Mean power spectra for subject C with the target stimulus level set at (**a**) 1.6 D, or (**b**) 3.1 D. Each curve is the mean of 5 individual power spectra. Pupil sizes are shown.

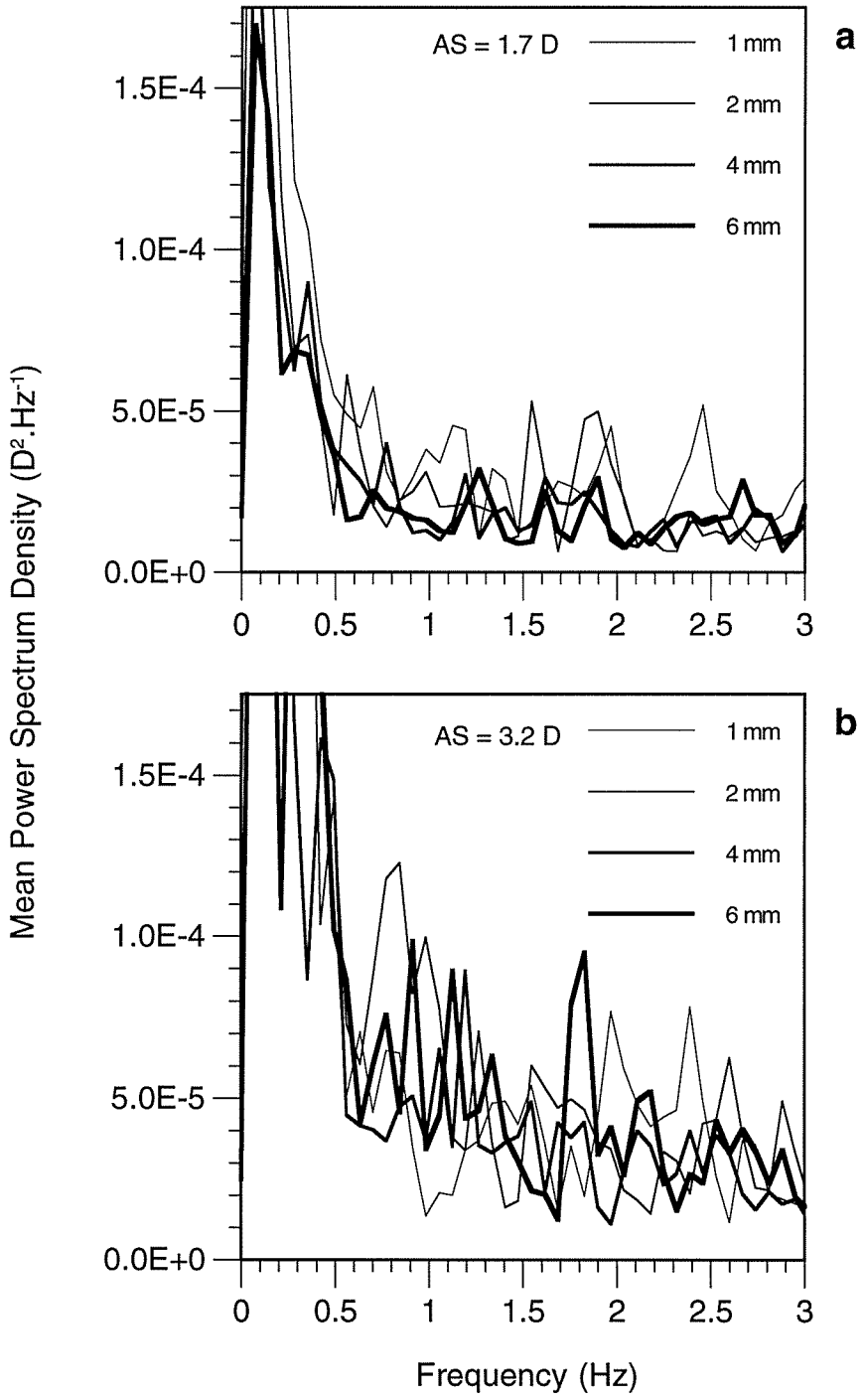


Figure 4.9. Mean power spectra for subject D with the target stimulus level set at (**a**) 1.7 D, or (**b**) 3.2 D. Each curve is the mean of 5 individual power spectra. Pupil sizes are shown.

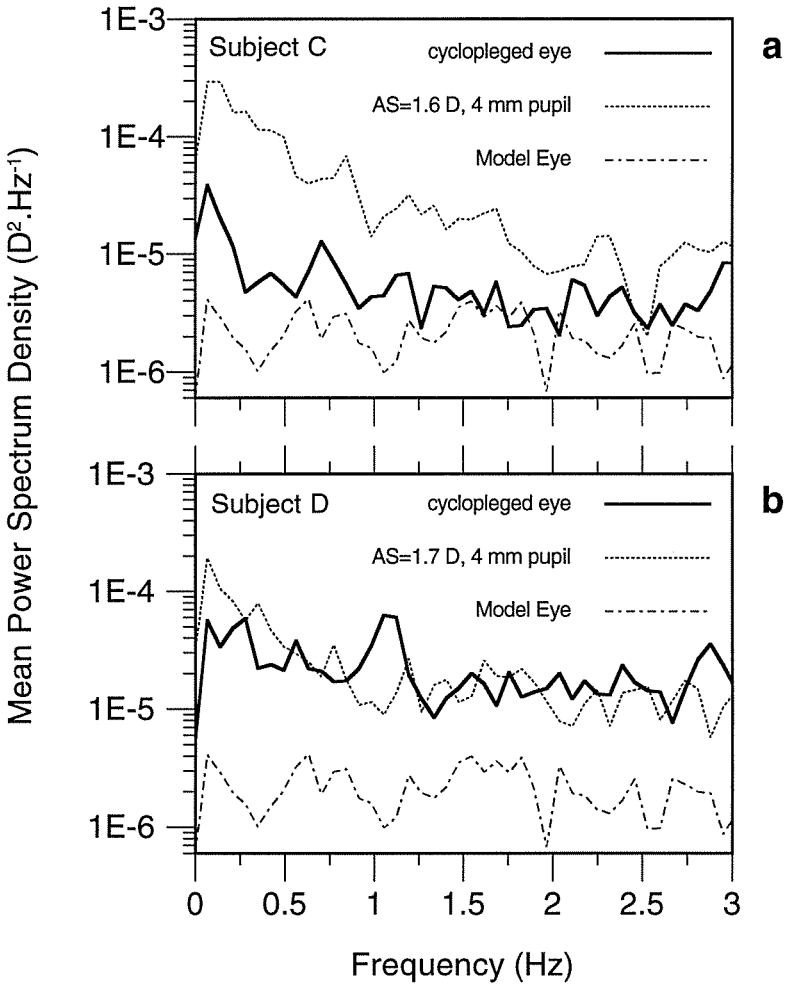


Figure 4.10. Mean power spectra for cyclopleged, non-cyclopleged and model eyes. Data for subject C is shown in part (**a**), and data for subject D is shown in part (**b**). The model eye data is from a Bausch and Lomb model eye. Mean curves for non-cyclopleged eyes and the model eye are the average of 5 individual power spectra. Mean curves for cyclopleged eyes are the average of 5 and 9 individual power spectra for subjects C & D respectively.

been sufficiently sensitive to detect small amplitude fluctuations of accommodation.

In the case of subject C, the accommodation in the non-cyclopleged eye is more noisy than in the cyclopleged eye, which may obscure the small amplitude high frequency fluctuations (Figure 4.10).

ILLUMINANCE EFFECTS

A change in 'equivalent luminance' of the target from 40 $cd.m^{-2}$ to 6 $cd.m^{-2}$ appears to have no effect on high frequency fluctuations with either pupil size, or on low frequency fluctuations with a 6 mm pupil (Figure 4.11). However, the low frequency fluctuations for a 1 mm pupil increase when the target 'effective luminance' is decreased. These observations were confirmed using partial correlations.

There is no significant partial correlation between high frequency effective deviation and 'equivalent luminance' controlling for both mean accommodation response level and pupil size ($r_{12.34} = 0.10, p = 0.40$). The partial correlation between low frequency effective deviation and 'equivalent luminance' controlling for both mean accommodation response level and pupil size is not significant ($r_{12.34} = -0.21, p = 0.07$). However, ignoring the 6 mm pupil data, there is a significant partial correlation between low frequency effective deviation and 'equivalent luminance' when controlling for mean accommodation level ($r_{12.3} = -0.37, p = 0.02$). Thus, in the main study, it is likely that smaller low frequency fluctuations would have been found with the 1 mm pupil if the target luminance had been adjusted to give an 'equivalent luminance' of 40 $cd.m^{-2}$. However, does the pupil still affect the low frequency fluctuations despite the effects of retinal illuminance? There is a significant partial correlation between low frequency effective deviation and pupil size when controlling for mean accommodation level, and when only using the high (40 $cd.m^{-2}$.) 'effective luminance' data ($r_{12.3} = -0.50, p = 0.001$). Thus, small pupils lead to an increase in low frequency fluctuations independent of the 'effective luminances' of the target in this study.

Mean and median power spectra for subject D in this control experiment are shown in Figure 4.12. Three medium to high frequency peaks are obvious in the power spectra of this subject. A peak in the power spectrum at about 1.2 Hz correlates with the subject's mean radial pulse of 1.3 Hz (76.5 $beats.min^{-1}$). A peak at about 0.6 Hz may be due to the respiration rate. There is also a peak at about 2 Hz in the power spectra. This peak appears to

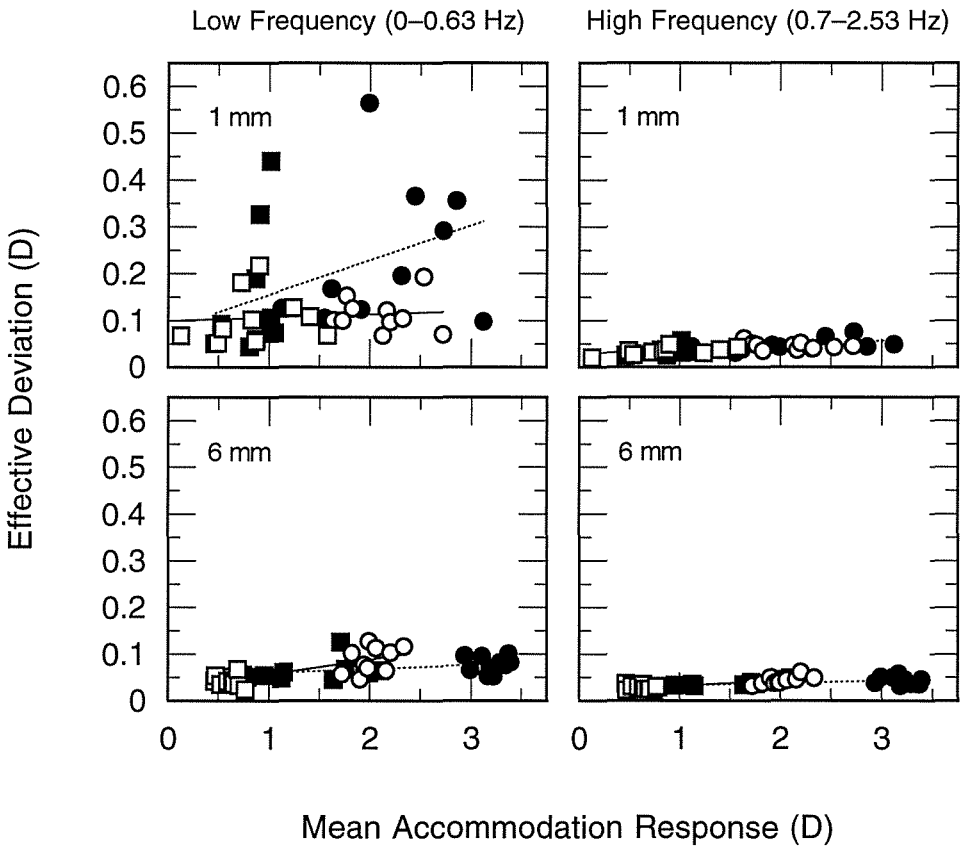


Figure 4.11. High and low frequency fluctuations of accommodation for subject D as a function of mean accommodation level. The effective deviation is a measure of accommodation fluctuations (equations 4.2, 4.3). Stimulus levels were 1.7 D (squares), and 3.2 D (circles). Open symbols denote data obtained with an 'equivalent luminance' of 40 cd.m^{-2}, and closed symbols denote data obtained with an 'equivalent luminance' of 6 cd.m^{-2}. The solid and dotted lines are best fit lines (by principal axis regression) to the high and low luminance data respectively.

increase for small pupils — exactly the opposite of what was found by Campbell, Robson and Westheimer[1] in their 1959 study! A comparison of the mean and median curves shows that in some cases the apparent peak in the *mean* power spectrum may be due to outlying responses with a particularly large 2 Hz fluctuation. This is because any outliers would have biased the mean power spectrum more than the median power spectrum.

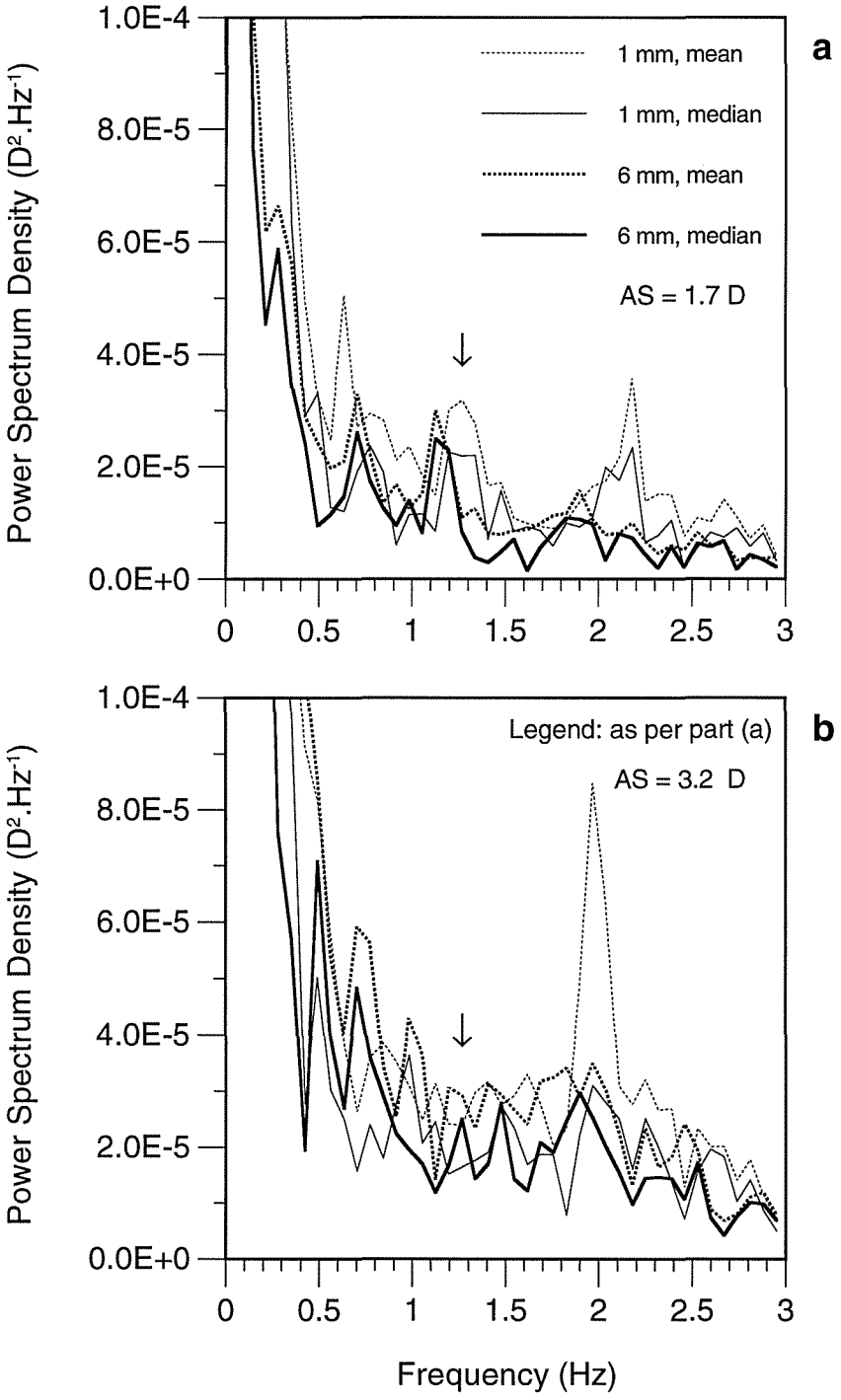


Figure 4.12. Mean and median power spectra for subject D obtained with an 'equivalent target luminance' of 40 cd.m^{-2}, and with a target stimulus level of either (**a**) 1.7 D, or (**b**) 3.2 D. Pupil sizes are shown. Each curve is the mean or median of 10 individual spectra. Note that dotted lines denote mean curves, while solid lines denote median curves. The arrows indicate the radial pulse frequency.

4.4. Discussion

Mean Accommodation Level and Fluctuations of Accommodation

Most of the subjects in this study showed larger high frequency fluctuations of accommodation at higher mean response levels, although only half of the subjects showed a significant increase in low frequency fluctuations at higher mean response levels. This general trend agrees with previous studies.[10,23] It has been hypothesised that the changes in the amplitude of accommodation fluctuations with mean accommodation level are related to the mechanical characteristics of the lens and ciliary body.[8-10] As the accommodation near and far points are approached, the lens is less capable of transmitting dynamic forces applied on it by the zonules and ciliary body.

It is interesting to note that accommodation fluctuations were not correlated with mean response level for subject C. This subject was the oldest in the study, and had a subjective amplitude of accommodation of 3.5 D. Accommodation fluctuations appear to be minimal near the far and near points,[10] and it may be that the closeness of the target stimulus levels of 1.6 D and 3.1 D to subject C's far point and near point respectively inhibited any changes in accommodation fluctuations. The effect of age on the fluctuations of accommodation has not yet been investigated.

Pupil Size and Fluctuations of Accommodation

In agreement with previous qualitative observations[12] and quantitative findings,[2] this study found that the low frequency fluctuations become larger with smaller pupils; but the high frequency fluctuations are independent of pupil size.

A control experiment showed that the pupil size does have an independent effect on low frequency fluctuations. This effect of pupil size is independent of the differences in retinal illuminance between the 1 mm and 6 mm pupil sizes used in this study. Retinal illuminance also had an independent effect on low frequency fluctuations for a 1 mm pupil. Gray

et al. found that low frequency fluctuations (with a fixed 5 mm pupil) are larger at low target luminances.[24]

PUPIL SIZE AND LOW FREQUENCY FLUCTUATIONS

The increase in low frequency fluctuations with smaller pupils lends support to the hypothesis that the low frequency fluctuations may be involved in the accommodation control process.[8,11] Gray *et al.* suggested that small pupils increase the accommodation system's requirement for low frequency modulation of the retinal image contrast.[25] This is consistent with calculated changes in the modulation transfer function with pupil size and accommodation error[11] — to obtain a given change in modulation of the retinal image contrast, accommodation needs to alter over a greater range with a smaller pupil. But does the accommodation control system purposely inject low frequency signals into the neural feedback pathway?

Most control models of accommodation do not inject a noise signal to simulate accommodation fluctuations. Exceptions are the models of Sun *et al.*[26] who injected Gaussian noise with a 0.3 s bandwidth, and Hung *et al.*[27] who included a 2 Hz sinusoidal fluctuation. Kotulak and Schor used a 2 Hz fluctuation to drive an accommodation error detector, however their model could also work with fluctuations of other frequencies.[28] Other known effects of pupil size on the characteristics of accommodation can be incorporated in present models. I mention these here, but they are unlikely to affect the fluctuations of accommodation for steady targets unless the accommodation controller gain makes the system unstable. The effects of pupil size on depth of focus[7] can be modelled with a dead space element (see for example Hung *et al.*[29]). Small pupils also reduce the stimulus–response slope of accommodation, with the largest effects occurring for pupils smaller than about 1 mm.[11,12,30,31] These changes can be modelled as changes in the accommodation controller gain. Ward and Charman[11] have suggested that the accommodation controller gain is dependent on depth of focus.

There is another explanation for the larger low frequency fluctuations of accommodation observed with small pupils that does not involve the purposeful injection of a fluctuating signal in the neural pathway of the accommodation system. Both this study and that of Gray *et al.*[2] did not sample accommodation for a sufficiently long period of time to resolve the low frequency changes. Gray and other's power spectra had a frequency resolution of 0.1 Hz, and they ignored fluctuations in the 0–0.3 Hz range. The power spectra in this study had a resolution of 0.07 Hz, and any low frequency drifts or slow apparently aperiodic changes in the accommodation response would have appeared as increased power in the first few bins of the power spectrum. The increased depth of focus afforded by a small pupil may allow subjects to use voluntary accommodation in an attempt to obtain a clearer image. Their accommodation could drift over a larger range before any subjective changes in clarity are observed. Also their awareness of the proximity of the target may also change with time. For example, with a very small pupil (0.5 mm) subjects can accommodate to a real target fairly accurately using nothing more than perceived distance as a cue.[32] In a Badal system there may be ambiguous and misleading proximal cues (see Chapter 3) which could lead to a 'manifest' proximal response with a small pupil. The important point is that these changes, because they have a cognitive origin would likely be aperiodic, and would appear in a power spectrum as low frequency spectral power. Some accommodation records in this study did show apparently aperiodic changes in accommodation. Thus, the low frequency fluctuations may not be a purposeful attempt to aid the steady accommodation response. Instead they may simply represent the voluntary, proximal and cognitive influences that become manifest due to the latitude offered by large depth of focus with small pupils.

When viewing a target at a close distance, the low frequency fluctuations are largest for a 2 mm pupil, but then decrease with a 1 mm pupil (Figure 4.5). This effect was not statistically significant, and was not observed by Gray *et al.* in their study at a lower accommodation stimulus level.[2] Nevertheless, it is interesting to speculate that these differences may be due

to effort made by the subjects to focus the target. Possibly with the pupils 2 mm and larger, the depth of focus is such that subjects can obtain a better focus if they make extra effort, but with the 1 mm pupil the depth of focus is so large that they do not bother to make an effort because it does not improve target clarity. The effort made with the 2 mm and larger pupils may make the accommodation response more variable, but is confined to slow (low frequency) changes in accommodation.

PUPIL SIZE AND HIGH FREQUENCY FLUCTUATIONS

Because this study integrated the power spectra over a wide high frequency range (0.7–2.53 Hz), it is not possible to comment on whether particular high frequency fluctuations are involved in accommodation control. However, Gray *et al.* have shown that the magnitude of high frequency peaks observed in their subjects are not correlated with pupil size. This adds support to the hypothesis that high frequency fluctuations are not under active neural control as an aid to steady state accommodation.[8]

A number of observations can be made about the accommodation power spectra obtained in this study. The multiple high frequency peaks observed in some subjects in the main study may be due to the small number of individual spectra contributing to each mean spectrum (Figures 4.6, 4.7, 4.9).[33] However, the mean spectra obtained for subject D in the illuminance control experiment do show definite multiple high frequency peaks. There is a peak at about 0.7 Hz possibly associated with the respiration rate,[a] a peak at about 1.2 Hz possibly associated with the pulse rate, and in some records a 2 Hz peak. This raises the question of whether in addition to the established pulse peak,[5,6] there may also be a higher 2 Hz peak representing accommodation system instability.[3]

It is interesting to note that a 2 Hz peak for subject D in the illuminance control experiment becomes larger with a smaller pupil (Figure 4.12), which is the opposite of the effect noted by Campbell *et al.*[1] However, subject B, when viewing a near target, shows a decrease in the 2 Hz peak with a

smaller pupil, in support of Campbell *et al.* (Figure 4.7b). A possible explanation for these apparently conflicting results relates to the intermittent nature of the 2 Hz oscillations. This is best demonstrated by the power spectra obtained for subject D when viewing a near target in the illuminance control experiment (Figure 4.12b). The *mean* power spectra seem to show an increase in the magnitude of the 2 Hz peak for a 1 mm pupil (from 0.026 D to 0.04 D real amplitude); however the *median* power spectra do not show this effect. This suggests that outlying runs can skew the mean power spectrum. Thus it may be that a person's accommodation system occasionally becomes unstable and exhibits a relatively larger 2 Hz oscillation. The power spectrum from such a response skews the mean power spectrum, and makes it appear as if the pupil size is influencing the 2 Hz fluctuations of accommodation.

The 2 Hz peak observed in the accommodation power spectra of some subjects in this study may represent a system instability as originally suggested by Stark *et al.*;[3] however in this present study I cannot rule out spurious readings due to misalignment of the eye in the optometer.

4.5. Summary

1. The magnitudes of both low frequency (0–0.63 Hz) and high frequency (0.7–2.53 Hz) fluctuations of accommodation increase with mean accommodation response level in most subjects.
2. Pupil sizes in the range 1 mm through 6 mm have no significant effect on the high frequency fluctuations of accommodation, but small pupils do lead to an increase in the low frequency fluctuations.
3. It has been previously hypothesised that low frequency fluctuations are used to aid the steady state accommodation response. However the increase in low frequency fluctuations with small pupils may instead be due to the increased latitude for voluntary, proximal and cognitive influences afforded by the large depths of focus for small pupils.

4. The magnitude of a 2 Hz peak in the accommodation power spectrum was found to increase with a smaller pupil for one subject and to decrease with a smaller pupil for another subject. Differences between the mean and median power spectra suggest that an occasional 2 Hz instability can skew the mean power spectrum. It may be that pupil size does not affect the 2 Hz fluctuations, but that these fluctuations occur occasionally because of some other factor.

Unpublished Manuscript

a. Collins, M., B. Davis and J. Wood. Microfluctuations of steady-state accommodation and the cardiopulmonary system.

References

1. Campbell, F.W., J.G. Robson and G. Westheimer. Fluctuations of accommodation under steady viewing conditions. *J. Physiol.* 1959, **145**, 579–594.
2. Gray, L.S., B. Winn and B. Gilmartin. Accommodative microfluctuations and pupil diameter. *Vision Res.* 1993, **33**(15), 2083–2090.
3. Stark, L.W., Y. Takahashi and G. Zames. Nonlinear servoanalysis of human lens accommodation. *IEEE Trans. Syst. Sci. Cybern.* 1965, **SSC-1**(1), 75–83.
4. Campbell, F.W., J.G. Robson and G. Westheimer. The control of accommodation in the human eye. *In: Proceedings of the 2nd International Congress on Cybernetics.* 1958. pp. 924–929.
5. Winn, B., J.R. Pugh, B. Gilmartin and H. Owens. Arterial pulse modulates steady-state ocular accommodation. *Curr. Eye Res.* 1990, **9**(10), 971–975.
6. Owens, H., B. Winn, B. Gilmartin and J.R. Pugh. Effect of a topical beta-adrenergic receptor antagonist on the dynamics of steady-state accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**(4), 99–104.
7. Campbell, F.W. The depth of field of the human eye. *Opt. Acta (Paris).* 1957, **4**(4), 157–164.
8. Charman, W.N. and G. Heron. Fluctuations in accommodation: a review. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 153–164.
9. Kotulak, J.C. and C.M. Schor. Temporal variation in accommodation during steady-state conditions. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1986, **3**(2), 223–227.
10. Miege, C. and P. Denieul. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 165–171.
11. Ward, P.A. and W.N. Charman. Effect of pupil size on steady state accommodation. *Vision Res.* 1985, **25**(9), 1317–1326.
12. Ward, P.A. and W.N. Charman. On the use of small artificial pupils to open-loop the accommodation system. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 191–193.
13. Mordi, J., J. Tucker and W.N. Charman. Effects of 0.1% cyclopentolate or 10% phenylephrine on pupil diameter and accommodation. *Ophthalmic Physiol. Opt.* 1986, **6**(2), 221–228.

14. Mordi, J.A., W.M. Lyle and G.Y. Mousa. Effect of phenylephrine on accommodation. *Am. J. Optom. Physiol. Opt.* 1986, **63**(4), 294–297.
15. Rosenfield, M., B. Gilmartin, E. Cunningham and N. Dattani. The influence of alpha-adrenergic agents on tonic accommodation. *Curr. Eye Res.* 1990, **9**(3), 267–272.
16. Jaanus, S.D., V.T. Pagano and J.D. Bartlett. Drugs affecting the autonomic nervous system. *In:* J.D. Bartlett and S.D. Jaanus eds. *Clinical Ocular Pharmacology*. 2nd ed. Boston: Butterworths, 1989. pp. 69–148.
17. Newcomb, R.D. and M.L. Priest. Systemic effects of ocular drugs. *In:* J.D. Bartlett and S.D. Jaanus eds. *Clinical Ocular Pharmacology*. 2nd ed. Boston: Butterworths, 1989. pp. 843–862.
18. Heron, G., B. Winn, J.R. Pugh and A.S. Eadie. Twin channel infrared optometer for recording binocular accommodation. *Optom. Vision Sci.* 1989, **66**(2), 123–129.
19. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin*. 1972, **77**(1), 54–64.
20. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.
21. Adams, C.W. and C.A. Johnson. Steady-state and dynamic response properties of the Mandelbaum effect. *Vision Res.* 1991, **31**(4), 751–760.
22. Pedhazur, E.J. *Multiple Regression in Behavioral Research. Explanation and Prediction*. 2nd ed. New York: Holt, Rinehart and Winston, 1982. pp. 97–134.
23. Denieul, P. Effects of stimulus vergence on mean accommodation response, microfluctuations of accommodation and optical quality of the human eye. *Vision Res.* 1982, **22**(5), 561–569.
24. Gray, L.S., B. Winn and B. Gilmartin. Effect of target luminance on microfluctuations of accommodation. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 258–265.
25. Gray, L.S., B. Winn and B. Gilmartin. Microfluctuations of accommodation below 0.6 Hz are likely to contribute to the maintenance of sustained accommodation [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1307.
26. Sun, F. and L.W. Stark. Switching control of accommodation: experimental and simulation responses to ramp inputs. *IEEE Trans. Bio.-Med. Eng.* 1990, **37**(1), 73–79.
27. Hung, G.K., J.L. Semmlow and K.J. Ciuffreda. Accommodative oscillation can enhance average accommodative response: a simulation study. *IEEE Trans. Syst., Man, Cybern.* 1982, **SMC-12**(4), 594–598.
28. Kotulak, J.C. and C.M. Schor. A computational model of the error detector of human visual accommodation. *Biol. Cybern.* 1986, **54**, 189–194.
29. Hung, G.K. and J.L. Semmlow. Static behavior of accommodation and vergence: computer simulation of an interactive dual-feedback system. *IEEE Trans. Bio.-Med. Eng.* 1980, **BME-27**(8), 439–447.
30. Ripps, H., N.B. Chin, I.M. Siegel and G.M. Breinin. The effect of pupil size on accommodation, convergence, and the AC/A ratio. *Invest. Ophthalmol.* 1962, **1**(1), 127–135.
31. Hennessy, R.T., T. Iida, K. Shiina and H.W. Leibowitz. The effect of pupil size on accommodation. *Vision Res.* 1976, **16**, 587–589.
32. Rosenfield, M., K.J. Ciuffreda and G.K. Hung. The linearity of proximally induced accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1991, **32**(11), 2985–2991.
33. Pugh, J.R., A.S. Eadie , B. Winn and G. Heron. Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic Physiol. Opt.* 1987, **7**(3), 321–324.

Chapter 5

Peripheral Stimuli to Accommodation

5.1. Introduction

The first aim of this study is to determine if the accommodation response to an extended target can be predicted from the responses to its constituent parts. The second aim is to investigate the roles of voluntary and 'reflex' components in the accommodation responses to peripheral target detail.

Does Peripheral Target Detail Assist Accommodation?

Many studies have demonstrated that accommodation can occur to peripheral targets, although these studies disagree over the extent of peripheral detail that can elicit an accommodation response (see section 1.5.4).[1-7]

Recently, Ciuffreda *et al.* investigated the effect of target size on accommodation.[6,8] They increased the diameter of a grating target and found that the steady accommodation response became more accurate up to about 3° or 4° radius, but did not improve any further for larger targets. Similar results were obtained with the central 0.5° radius of target detail removed. For small diameter targets, the accommodation response was poorer with the central 0.5° of detail removed, although the absence of central detail had little effect on accommodation accuracy when the outer radius of the target was large (about 4°). These results suggest that the small central region of the visual field is not necessary for an accurate response, and that peripheral target detail can make up for the absence of central detail. The results also suggest that there is pooling of blur information from the retinal cones in the central and paracentral visual field to the accommodation control centres.

When I first encountered the study of Ciuffreda *et al.* it reminded me of some calculations I had once made on the responses to conflicting targets. I became interested in the connections between this study[6,8] and my calculations because it initially seemed that the experimental findings could be predicted on the basis that the accommodation response to a target can be predicted from the responses to its constituent parts.

At that time I was considering a simple steady state control model with multiple inputs as shown in Figure 5.1. For this proportional control model it can be shown by simple algebra that

$$AR = ABIAS + \left(g_1(AS_1 - AR) + g_2(AS_2 - AR) + \ldots + g_i(AS_i - AR)\right) . \quad (5.1)$$

Simplifying and solving for AR yields

$$AR = \frac{\sum AS_i g_i + ABIAS}{1 + \sum g_i} , \quad (5.2)$$

where AR is the accommodation response, AS_i is the accommodation stimulus level of target i, g_i is the open-loop accommodation controller gain for target i by itself, and ABIAS is the accommodation resting level.

The problem I considered was whether this model could predict responses to multiple targets. I considered the case where all targets are at

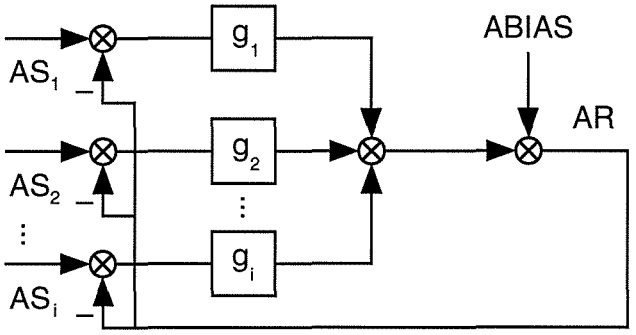


Figure 5.1. A simple steady state control model of multiple inputs to the accommodation system. See the text for a description of the components of the model.

the same stimulus level and found that the predicted accommodation response becomes more accurate as the number of targets is increased. For example, if all targets are presented at 6 D, all have accommodation controller gains of +9, and the ABIAS level is +1 D, then the accommodation responses for 1, 2, 3, and 4 such targets are 5.5 D, 5.74 D, 5.82 D, and 5.86 D respectively. This increase in accommodation accuracy seems to fit with general wisdom that complex targets are better accommodation stimuli. However, there is a problem with the model. There is no way of knowing that the accommodation system sees each target as a *single* target — that is, does the accommodation system, for example, see 1, 2, and 3 targets or does it see 100, 200, and 300 target 'bits'. I therefore considered at the time that the predictions of this model are simply a mathematical oddity. However, this problem can be solved if the accommodation system samples visual space in discrete 'bits', and if the size of these 'bits' can be ascertained.

A THEORETICAL MODEL

It is possible that the primary visual cortex is involved in the accommodation process (see sections 1.3.1 & 1.3.2). There is a close spatial mapping between the retina and visual cortex, the primary unit of which is

the cortical hypercolumn.[9] The neurons of the hypercolumns perform a patch-by-patch spatial filtering of visual space, which may be of use to the accommodation system.[10,11] Schwartz has estimated that the basic 'unit' of spatial vision in the human cortex (which possibly corresponds to the hypercolumn) has a width of about 2 mm.[9] Thus the hypercolumn provides a way of sampling the accommodation target in a patch-by-patch manner. At present there is no evidence that accommodation actually does sample visual space in discrete 'bits' using the hypercolumns, however it is a plausible theory.

To develop a theory of the response to peripheral targets, I start with the model shown in Figure 5.1 and described by equation (5.2). For simplicity it is assumed that the target is sampled along the horizontal meridian by a series of i adjoining cortical spatial units. Note that the responses of all the cortical units in a circle of equal eccentricity in visual space are considered as if they are only one cortical unit on the horizontal meridian (Figure 5.2a). This is necessary because no-one has yet determined the accommodation response to very small targets over the entire visual field, but data is available on the accommodation response to disc targets. Note also that in Figure 5.2b each unit samples a narrow *ring* of target detail, *not* a vertical stripe of target detail. Now if the target is at one stimulus level then $AS_i = AS$ for all i. Suppose that target detail is present for all cortical spatial units between units j and k (Figure 5.2b). The sum of the open-loop accommodation controller gains between cortical units j and k is given by

$$\sum_{i=j}^{k} g_i = \sum_{i=j}^{k} g(ecc_i) \ , \tag{5.3}$$

where $g(ecc_i)$ is the open-loop accommodation controller gain at a discrete eccentricity in visual space. Equation (5.2) then becomes

$$AR = \frac{AS.\sum_{i=j}^{k} g(ecc_i) + ABIAS}{1 + \sum_{i=j}^{k} g(ecc_i)} \ . \tag{5.4}$$

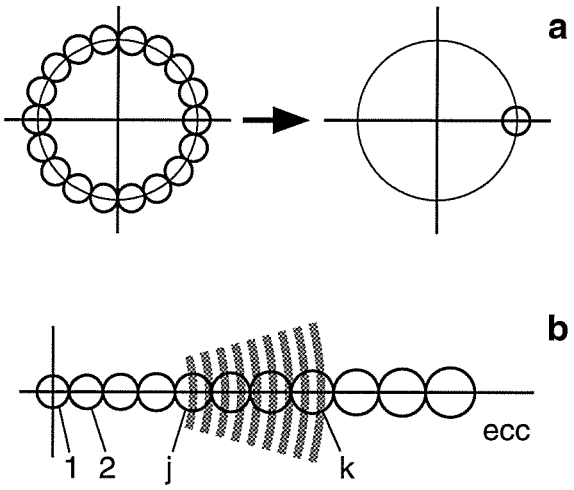


Figure 5.2. Schematic representation of cortical spatial units sampling a target in visual space. Part (**a**) shows how the cortical units of equal eccentricity are modelled as a single unit on the horizontal meridian. Part (**b**) shows how the hypothesised cortical units may sample visual space. Each unit samples a ring of target detail. 'Ecc' is the eccentricity in visual space.

Two pieces of information are needed to use the above equation: (1) the open-loop accommodation controller gain as a function of eccentricity in visual space; and (2) the size of the cortical units in terms of angular extent in visual space.

The accommodation controller gain as a function of eccentricity can be calculated from the data of Bullimore and Gilmartin.[4] They provided a plot of the accommodation stimulus–response function slope as a function of eccentricity (degrees). A linear regression equation fitted to their data between 0.5° and 10° is given by

$$m = b.ecc + a \ , \tag{5.5}$$

where m is the accommodation stimulus–response function slope, ecc is the eccentricity of target detail in degrees radius, $b = -0.0683$ degree^{-1}, and $a = 0.9269$.

Now for a single target and the simple accommodation control system of Figure 5.1, the relationship between open-loop accommodation controller gain (g) and stimulus–response slope (m) is given by

$$m = \frac{g}{1+g} . \tag{5.6}$$

From equations (5.5) and (5.6) it can be shown that the open-loop accommodation controller gain is given by

$$g = \frac{b.ecc + a}{1-(b.ecc + a)} . \tag{5.7}$$

Open-loop accommodation controller gain as a function of eccentricity calculated from equation (5.7) is shown in Figure 5.3.

The next step is to determine the areas of visual space sampled by the cortical spatial units. The cortical magnification factor (mm/degree) describes the length of visual cortex (mm) per degree of visual space. Along the nasal meridian of the visual field the human cortical magnification factor was estimated by Rovamo and Virsu[12] to be given by

$$CMF_{nasal} = \frac{7.99}{1+0.33.ecc+7\times10^{-5}ecc^3} . \tag{5.8}$$

Dropping the ecc^3 term results in only small errors (+3.8% at 15°), and gives

$$CMF_{nasal} = \frac{7.99}{1+0.33.ecc} . \tag{5.9}$$

Integrating equation (5.9) with respect to eccentricity yields the cortical length (L) as a function of eccentricity:

$$L = 24.21.\ln|1+0.33.ecc| . \tag{5.10}$$

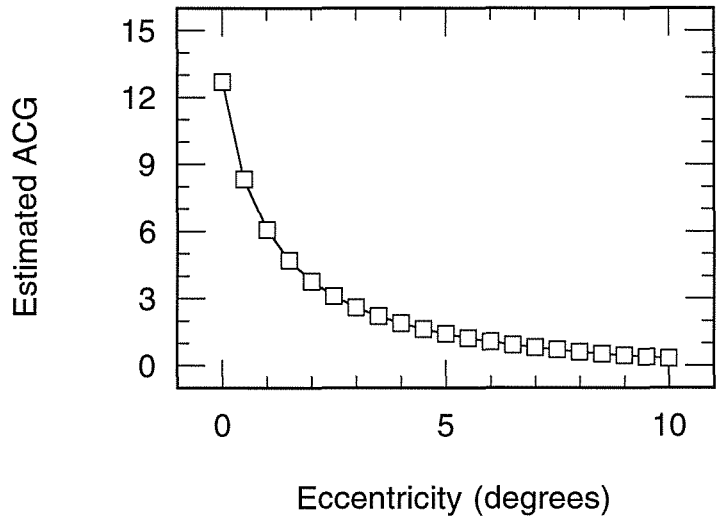


Figure 5.3. Predicted open-loop accommodation controller gain as a function of eccentricity based on the peripheral accommodation data of Bullimore and Gilmartin.[4] See equations (5.5) through (5.7) and associated text.

Schwartz has estimated that the cortical spatial unit has a cortical length of about 2 mm.[9] Therefore assuming that the first cortical unit is centred on the centre of the visual field, then the inside borders of adjacent units will be located at distances of 1, 3, 5, 7,... mm along the cortex (Figure 5.4). These cortical lengths can be converted to angles in visual space by rearranging equation (5.10) to give

$$ecc = \frac{e^{L/24.21} - 1}{0.33} . \qquad \textbf{(5.11)}$$

I applied the above theory (note equations 5.4, 5.7 and 5.11) to the data of Ciuffreda *et al.* (Figure 5.5).[6] The predicted responses show a similar trend to the experimental responses, although the increase in accommodation accuracy with eccentricity predicted from theory was much smaller than found experimentally. This may relate to the adequacy of the targets in the two studies, and if a smaller value of b is used in equation (5.7), results qualitatively similar to Ciuffreda *et al.* are found. The theoretical model also correctly predicts the pattern of experimental data for the target with central detail removed.

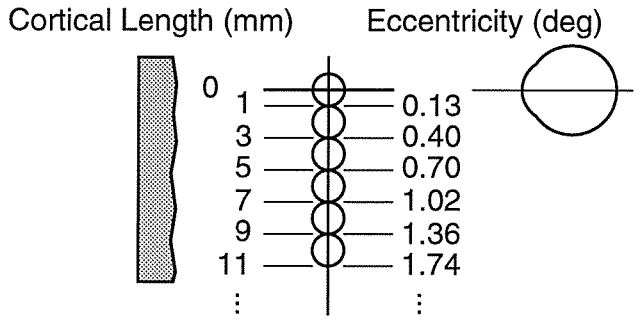


Figure 5.4. Schematic representation of conversion of visual cortical lengths to eccentricities in visual space using equation (5.11).

Although the theoretical model works reasonably well in predicting the *pattern* of responses to peripheral targets, it makes many assumptions which may or may not be valid. These assumptions are: (1) the visual cortex lies in the accommodation neural pathway and that any alternate pathways do not exist or are unimportant; (2) the spatial cortical units have a width of 2 mm, and only sample discrete portions of visual space; (3) depth of focus is negligible in central and peripheral vision; (4) the subjects of both Bullimore and Gilmartin[4] and Ciuffreda *et al.*[6,8] had equivalent accommodation function. Assumption (1) may be correct but the afferent neural pathways of accommodation have not been established. Assumption (2) may be incorrect because it is unlikely that there would be *no* overlap in the regions of visual space sampled by the neurons of adjacent hypercolumns. Nevertheless, this violation may not be serious. Violation of the assumption (3) regarding depth of focus is probably the most serious. Depth of focus probably increases in peripheral vision and thus any small contributions peripheral cones might have made would not occur because of their insensitivity to defocus. Later in this study I develop a dynamic control model that does include depth of focus.

In summary, the simple model developed in this section does reasonably well in predicting responses to extended target, but it needs refinement. The model does agree with the results of Ciuffreda *et al.* that accommodation performance improves with larger targets.[6,8]

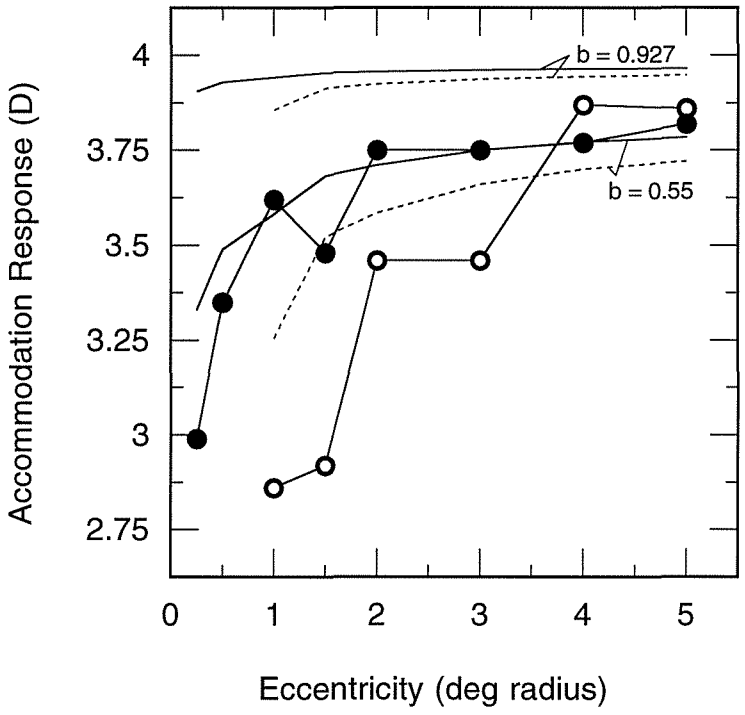


Figure 5.5. Accommodation response as a function of outer radius of either a patterned disc target, or a patterned annulus target with central 0.5° radius removed. Circles are replotted experimental data from Ciuffreda *et al.*[6] Filled circles are data for disc targets, and hollow circles are the data for annulus targets. Two sets of theoretical data are shown: (1) predicted accommodation responses based on the peripheral accommodation data of Bullimore and Gilmartin[4] (b = 0.927); (2) predicted accommodation response based on an arbitrary lower value for the constant b (b = 0.55) (see equation 5.7).

FIRST AIM OF THIS STUDY

In this study I determine the dynamic accommodation characteristics for three targets to see if the responses to combinations of these targets can be predicted from the responses to the individual targets. I also measure peripheral visual acuity and depth of focus to see how these relate to peripheral accommodation performance. By collecting all these data on the same subjects I overcome the limitations imposed by cross-study comparisons, as in the preceding theoretical analysis.

'Reflex' Responses to Peripheral Targets

All studies of peripheral stimuli to accommodation to date have used steady targets or predictable dynamic targets (see section 1.5.4.3). With these targets there is the possibility that subjects may use voluntary accommodation to obtain a better accommodation response. Thus it is difficult to determine whether 'reflex' responses can occur to the blur of peripheral targets, or whether the responses to peripheral target simply result from voluntary accommodation. One way to reduce voluntary accommodation effects is to use sinusoidal target motion. If a suitably high speed of target motion is used then the subject has no time to make voluntary trial-and-error hunting movements of accommodation. The subject may intermittently make a voluntary focus change in the correct direction, but the sinusoidal motion is too fast for the subject to consistently make synchronous changes in focus. If it were found that accommodation occurred for *slowly* moving peripheral targets but not for *quickly* moving peripheral targets then this would suggest that subjects use voluntary accommodation to focus on steady peripheral targets. The predictable target motion of a sinusoidal target may allow better accommodation responses than random target motion,[13] however the apparatus in this study could not provide completely random dynamic stimuli.

SECOND AIM OF THIS STUDY

The second aim of this study is to compare accommodation responses to both slowly and quickly moving sinusoidal targets at various eccentricities to see if there is evidence for voluntary accommodation to the slowly moving targets.

5.2. Methods

Subjects

Two subjects participated in the study. Both were highly experienced as observers in accommodation experiments and were familiar with the

experimental apparatus. The subjects were aged 24 and 40 years, and had right eye refractive errors and visual acuities (Bailey–Lovie Chart) of RE -1.87 DS (6/4.8) and RE -2.00 DS (6/4.8) respectively. Both had normal central (10°) visual fields in their right eyes by static computerised perimetry, and their past ocular histories were normal (subject B suffered central serous retinopathy in his left eye three years previous but the right eye was not affected). Routine procedures were used to ensure that the topical ocular drugs used in this study could be safely used with the particular subjects (section 4.2).

Apparatus

Accommodation was measured dynamically with a modified Bausch and Lomb Ophthalmetron sampling along the vertical meridian of the right eye (see Appendix B). Targets were presented to the subject's right eye using a Badal stimulus system mounted on top of the Ophthalmetron (Appendix B). The Badal system prevented the subject from using proximal cues to accommodation. Targets were presented at a luminance of 40 $cd.m^{-2}$ and were viewed through a 5 mm artificial pupil placed at an artificial pupil plane in the Badal system. The limiting field stop of the Badal stimulus system is about 10° wide, and provides a vergence of +8.3 D at the eye. Thus for the two myopic subjects in this study, the blurred edge of the field was about 10 D beyond their far points and would not have provided a stimulus to accommodation. A Canon Autoref R-1 optometer was used to measure the subjects' dark focuses of accommodation (see Appendix A). Dark focus was not measured with the Ophthalmetron because it could not provide a completely dark field.

TARGETS

Accommodation Targets

The targets were discs and annuli filled with a 4 $cycle.degree^{-1}$ vertical and horizontal square wave pattern (Figure 5.6). The annuli were designed so that they could be superimposed on the smallest disc to make progressively

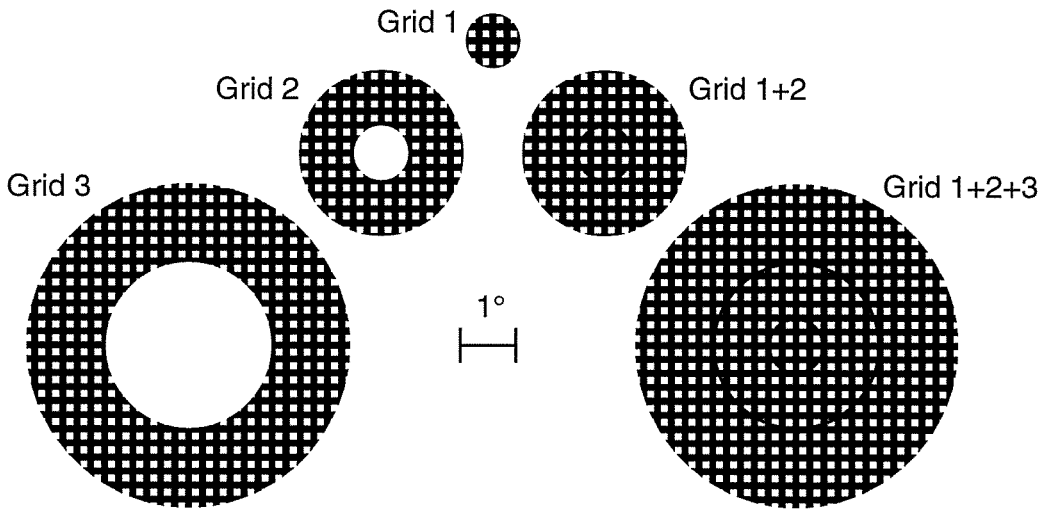


Figure 5.6. Grid targets used as accommodation targets. Note that the centres of Grids 2 and 3 were drilled out and so there was no central detail in these targets that could act as a stimulus to accommodation. The inside edges of the Grid 2 and Grid 3 targets had a visible abrasion zone about 3 minutes arc wide, caused by the drilling process used to make the targets. This abrasion zone is simulated by narrow lines in the Grid 1+2 and Grid 1+2+3 targets.

larger disc targets. In this way it was possible to compare the accommodation response to a composite target with the responses to its constituent parts. The 4 cycle.degree^{-1} grating detail should have provided a good stimulus to accommodation,[14,15] at least in central viewing. The outer radii of the Grid 1, Grid 2 and Grid 3 targets were 0.5°, 1.5° and 2.9° respectively. It would have been desirable to measure accommodation further into the periphery but this was prevented by the size of the field stop in the Badal system (10° diameter).

I produced the grids as high contrast black/white 35 mm photographic transparencies (Kodak Ortholith) for presentation to the subjects in the Badal stimulus system. Note that the centre portions of the Grid 2 and 3 transparencies were drilled or punched out so that they provided *no central detail which could act as a stimulus to accommodation.*

Visual Acuity Targets

A series of British Standard 5 × 4 Snellen letters (D, E, F, H, N, P, R, U, V, Z) were produced according to the Bailey–Lovie size progression.[16,17]

Procedures

OPHTHALMETRON CALIBRATION AND DEPTH OF FOCUS ESTIMATES

I performed individual calibrations of Ophthalmetron voltage output to subjective refraction for each subject while their right eye was cyclopleged with cyclopentolate (see section B.5). This was necessary to convert Ophthalmetron voltage output to accommodation readings. Right eye subjective amplitudes of accommodation were just 0.9 D and 0.6 D for subjects A and B respectively (Rodenstock Hand Optometer, Rodenstock, Munich).

I then estimated the subjective depth of focus for all five grid targets. The subject's left eye was fully patched and the subject viewed the grid targets through a 5 mm pupil at the artificial pupil plane of the Badal stimulus system. I first determined the best focus position of the Grid 1 target. I placed the target in Arm 1 of the Badal system (see Figure B.3) at a position well beyond the subject's far point, and then moved the target closer to the subject in 0.1 D steps. The subject's task was to report when the target first became blurred after it had been clear. I recorded the last position of clear focus before first blur. I also performed a trial with the target initially closer than the subject's far point and moving away form the subject. The order of these trials was counterbalanced.[18] I calculated the best focus position as the mean of the two blur threshold points, and then set the target at this best focus position. The reason for setting the target at this position of mean defocus is that depth of focus varies with mean defocus,[19,20] and a standard position is required for consistency.

I then determined the subjective depth of focus for all five grid targets separately by oscillating the target in a sinusoidal motion at 1 Hz about the best focus position. I altered the amplitude of the sine motion in a staircase

manner to determine the depth of focus, using both ascending and descending staircases. The amplitude of the sine wave could be altered in increments of 0.1 D. I had the subject listen to music in stereo headphones so that the faint sounds of the moving target could not be heard. The subject's task was to look at the centre of the grid pattern (even if it was blank in the cases of Grid 2 and Grid 3) and state whether the clarity of the target was changing or not changing.

VISUAL ACUITY MEASURES

In the next session I determined visual acuity for single letters at eccentricities of 0°, 0.5°, 1.5° and 2.9° radius, corresponding to central acuity and the outer radiuses of Grids 1, 2 and 3 respectively. Acuity was measured along the nasal horizontal meridian of the right eye. The subject viewed the letters against a white background of luminance 41–43 $cd.m^{-2}$, monocularly with their fully corrected right eye, and through natural pupils of between 4–5 mm. Thus, viewing conditions closely matched those in which accommodation was later measured. A method of constant stimuli was used to determine central and peripheral visual acuity. Presentation at the various eccentricities was counterbalanced,[18] letter sizes were presented pseudo-randomly, and the actual letters were presented randomly. Subjects were forced to report a name for the letter they were viewing, even when the letters were well below threshold.

PRACTICE SESSION AND DETERMINATION OF LINEAR RANGE OF STIMULUS–RESPONSE FUNCTION

Before the session, 1 drop of 2.5% phenylephrine (preceded by 1 drop 0.4% benoxinate) was instilled in the right eye to ensure that during measurements the eye pupil was greater than the 5 mm artificial pupil of the Badal stimulus system, and also to reduce the effects of pupil size on the Ophthalmetron output signal (see section B.8). The effect of this dose of phenylephrine on accommodation is small (see section 4.2). The subject was first given informal practice at accommodating to step changes of the various

grid targets. They were also given practice at the more difficult task of paying attention to the peripheral detail of the Grid 2 and Grid 3 targets.

To estimate the linear range of the accommodation stimulus–response function, I presented the Grid 1+2+3 target to the subject in the Badal system at positions ranging from beyond their far point to closer than their near point at 0.5 D intervals. At each position I sampled the accommodation response at 5 Hz for 5 seconds. The subject was instructed to 'look at the centre of the grid pattern and concentrate on the grid pattern'. The linear range determined in this way is for a target that provides a good stimulus to accommodation, and it may be that the linear range is smaller for the grid targets that provide only peripheral detail to accommodation, although no research has been done on this question.

MAIN SESSIONS

Prior to starting each session, 1 drop of 0.4% benoxinate and 1 drop of 2.5% phenylephrine were instilled in the subject's right eye. While the subject's eye was dilating, the dark focus was measured using the Canon Autoref R-1 optometer. The subject dark adapted in either a 3.8 m or 6.7 m laboratory for 5 minutes to allow any tonic adaptation effects to subside. With the room still dark, a number of accommodation readings was then made with the Autoref while the subject was instructed to 'look straight ahead towards the end of the room.' Two dim peripherally located eyefront illuminating lamps were used intermittently to align the eye (see section A.1).

When the subject's pupil had sufficiently dilated I commenced the main trials. The main trials were grouped in 4 blocks. Blocks were either run on separate days, or two blocks were run on one day with a rest period between the blocks. In each block there was one presentation of each combination of the 5 grid targets (see Figure 5.6) and the 3 temporal frequencies of target motion (0.02 Hz, 0.2 Hz and 0.5 Hz). Trials within a block were randomised, but with the constraint that the presentations for each individual target and frequency were not too clustered towards the start or the end of the block.

Table 5.1. Description of experimental runs for each temporal frequency of target motion.

	Temporal Frequency (Hz)		
	0.02	*0.2*	*0.5*
Pre-cycles	0*	2	4
Cycles	1	8	16
Total Run Length (s)	60	50	40

* There were no pre-cycles for the 0.02 Hz trial, but instead the subject adapted to the steady target for 10 seconds. For all three frequencies, accommodation was not recorded during the pre-cycle period.

Subjects viewed the various grid targets and were instructed:

> If there is detail in the centre of the pattern, look at the centre of the grid pattern and concentrate on the grid pattern. But if the centre of the pattern is blank, look at the centre of the grid pattern, concentrate on the pattern with your side vision, but do not look over at the pattern.

A 'view the target naturally' instruction (see Chapter 3) would have been inappropriate in this study because attending to peripherally located detail is not a natural task. Also, the instruction in this study avoids any reference to focusing because accommodation responses to dynamic targets tend to be more erratic when subjects try to *focus* on the target rather than simply *attend* to the target.[13]

The subject was presented with sinusoidal target motion within the linear ranges of their accommodation stimulus–response function. The peak-to-peak amplitude of target motion was 2 D for subject A and 1.4 D for subject B. In each run, there was an adapting period to allow the subject to 'latch on' to the target. After this period the accommodation response was sampled at 20 Hz. An outline of each run is given in Table 5.1. Subjects were allowed to blink during a run, and these blinks were later edited out of the accommodation records.

Analysis

OPHTHALMETRON CALIBRATION EQUATION

Calibration equations relating Ophthalmetron voltage output were calculated for each subject (see section B.5). Spectacle refraction was converted to an ocular refraction for infinite viewing distance and referred to an arbitrary entrance pupil of the eye 3.05 mm behind the corneal vertex (section E.2).[16]

VISUAL ACUITY

Probability of recognition curves were determined as a function of logMAR letter size for each eccentricity. Probit analysis was used to determine an 85% correct recognition rate, without correction for the small probability (≈10%) of guessing a letter.

ACCOMMODATION STIMULUS AND RESPONSE

The values of accommodation stimuli and responses were calculated using equations given in Appendix E. The linear range of the accommodation stimulus–response function determined by eye was 2 D wide and 3.5 D wide in subjects A and B respectively. This linear range value refers to the range of *stimuli* for which there is a linear relationship between stimulus and response.

Accommodation response gain and phase lag were calculated for the accommodation responses to sinusoidal target motion. Firstly, blinks were edited from the records in the following manner. The start and end of the blink contaminated data were located by eye and deleted. A third order polynomial was then fit to the 15 data points immediately prior to and following the blink, and this equation used to fill in the deleted data. In no case did this procedure remove more than 4.1% of the original data set.

The Fast Fourier Transform (Microsoft Excel[21]) was used to determine response gain and phase lag. Samples of 1024 points, 512 points, and 512 points were taken from both the target stimulus and accommodation

response records obtained for target temporal frequencies of 0.02 Hz, 0.2 Hz and 0.5 Hz respectively. The accommodation response *gain* was calculated as

$$gain = \frac{|z_{AR}|}{|z_{AS}|}, \tag{5.12}$$

where $|z_{AR}|$ is the modulus of the complex value of the Fast Fourier Transform of the accommodation response, and $|z_{AS}|$ is the modulus of the complex value of the Fast Fourier Transform of the accommodation stimulus, both at the frequency of target motion. No correction was made for background noise in the accommodation record or for the gain characteristics of the accommodation signal amplification (see section B.3 & Figure B.4). The accommodation response phase lag was calculated as

$$\theta = \tan^{-1}\left(\frac{y_{AR}}{x_{AR}}\right) - \tan^{-1}\left(\frac{y_{AS}}{x_{AS}}\right), \tag{5.13}$$

where y and x are the imaginary and real components respectively of the complex value of the Fast Fourier Transform at the frequency of target motion.

The Fast Fourier Transform was not applied to the original accommodation stimulus and response data. Instead, the mean response and any linear trend were first removed from the data before analysis using linear regression. This was particularly important for the 0.02 Hz records where the 0.02 Hz bin was the first bin of the power spectrum: the mean level and a linear trend might have otherwise 'spilled over' into the 0.02 Hz frequency bin. Low frequency aperiodic changes may have still appeared in the 0.02 Hz bin, although 0.02 Hz trials with aperiodic low frequency changes (by visual inspection) were discarded.

Gains and phase lags were calculated for each of the 4 runs (in a few cases, 2 or 3 runs) made with a particular target – temporal frequency combination, and then were vector averaged to give a mean gain and phase lag. Individual gain and phase lags were generally consistent across experimental blocks, although phase lags varied in some trials.

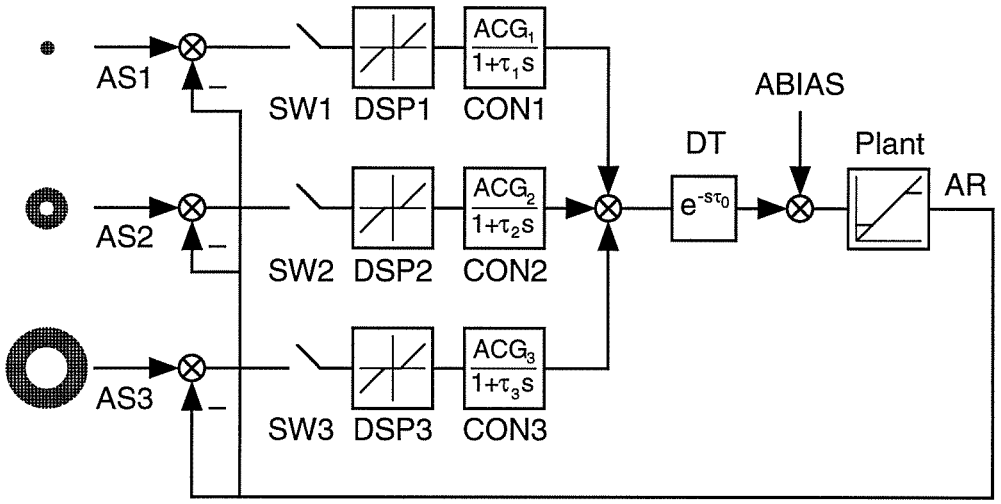


Figure 5.7. Control model of dynamic responses to the central and peripheral targets used in this study. See text for details of model components, and Table 5.2 for model parameters. Key: accommodation stimuli (AS1, AS2, AS3); switches (SW1, SW2, SW3); dead space elements (DSP1, DSP2, DSP3); controllers (CON1, CON2, CON3); accommodation controller gains (ACG1, ACG2, ACG3); controller time constants (τ_1, τ_2, τ_3); dead time element (DT); system dead time (τ_0); accommodation resting level (ABIAS); accommodation plant (Plant); accommodation response (AR). Note that 's' in this figure is the complex frequency variable used in Laplace transforms.

CONTROL MODEL OF ACCOMMODATION TO PERIPHERAL TARGETS

A control model was developed to model the dynamic responses to central and peripheral targets and their combinations (Figure 5.7). This model is similar to the static model developed in the Introduction to this chapter (see Figure 5.1). An advantage of this dynamic model is that it includes measures of depth of focus for the central and peripheral targets. Also, the model does not assume sampling by the cortex but simply assumes that there is patch-by-patch sampling somewhere in the neural pathways of accommodation, wherever those pathways may be.

The model has three accommodation stimuli (AS1, AS2 and AS3) corresponding to the stimuli provided by the Grid 1, Grid 2 and Grid 3

targets respectively. In this experiment the accommodation stimuli were all at the same level. The output of the system is the accommodation response (AR). Responses to Grid 1+2 and Grid 1+2+3 are obtained by opening or closing the appropriate switches (SW1, SW2, SW3). The model includes the experimentally determined depth of focus for each target (DSP1, DSP2, DSP3). The controllers are first order elements and are shown in Laplace notation (CON1, CON2, CON3). The controllers are leaky integrators (see section 1.7.1.1). The respective accommodation controller gains (ACG1, ACG2, ACG3) and controller time constants (τ_1, τ_2, τ_3) were estimated by a trial and error method (described below). The outputs of the controllers sum linearly at a summing junction. I used three separate controllers (rather than a common controller after the dead time element) because it is not known that the time characteristics of accommodation are the same in central and peripheral vision, and there is a suggestion that peripheral accommodation may be slower.[3] A representative value of 0.35 second was used for the accommodation dead time (τ_0).[22] It is assumed (in the absence of available data) that the dead time is similar in both central and peripheral vision. (The dead time is the reaction time of the accommodation response. See section 1.2.3.1) The experimentally determined accommodation resting level (i.e. dark focus) is represented in the model by the ABIAS input. The plant represents the far points and near points of accommodation. The accommodation model parameters used in this study are summarised in Table 5.2.

Model Implementation

The control model in Figure 5.7 was implemented with the Tutsim™ block diagram simulation language (Tutsim Products, Palo Alto, CA). A model listing is given in section D.1. The switches were modelled simply by setting the respective accommodation controller gains to zero. The plant was not included, because the stimuli in this experiment were always well within the accommodation near and far points.

The dead space values (DSP1, DSP2, DSP3) and the accommodation dark focus (ABIAS) were determined experimentally. A representative value of

Table 5.2. Accommodation model parameters

Model Parameter	*Subject*	
	A	*B*
Depth of Focus*		
±DSP1	0.28	0.19
±DSP2	0.34	0.27
±DSP3	0.56	0.84
Controller Parameters†		
ACG1	4.75	8
ACG2	3.25	7
ACG3	5	12
τ_1	6.5	7
τ_2	5	8
τ_3	5	6
Dead Time‡		
τ_0	0.35	0.35
ABIAS*	0.56	0.5§

* Experimentally determined parameters. † Model parameters determined by trial-and-error to fit experimental accommodation responses. ‡ Representative literature value. § The dark focus values measured for subject B in this experiment were lost, so the mean dark focus value obtained for this subject in Chapter 8 was used.

350 millisecond was used for the dead time (DT).[22] With these parameters in place, the responses to an almost steady target (0.02 Hz) were used to estimate the accommodation controller gains (ACG1, ACG2, ACG3) for the Grid 1, Grid 2 and Grid 3 targets separately. An initial guess of the value of the time constant of 6 seconds was used in this early analysis.[2] The controller gain was adjusted in a trial-and-error method to best fit the experimentally determined gain by eye. With the accommodation controller gains estimated, the time constants (τ_1, τ_2, τ_3) were then altered in a trial-and-error method to best fit (by eye) the experimentally determined gains at various frequencies

of target motion. I did not try to fit the experimentally determined phase lags.

5.3. Results

Peripheral Visual Acuity

Visual acuity (85% correct recognition) becomes poorer with eccentricity, as expected from previous research (Figure 5.8).[23-26] Subject A has better acuity than subject B at all eccentricities. For both subjects, central acuity by the method of constant stimuli shown in Figure 5.8 is between 1 and 2.5 lines worse than conventional Bailey–Lovie chart acuity (6/4.8 for both subjects). This could be partly due to both subjects' experience with the Bailey–Lovie chart.

Peripheral Depth of Focus

Perceptual depth of focus increases for more peripheral target detail (compare Grid 1, Grid 2 and Grid 3 values in Figure 5.9a). Depth of focus values for composite targets (Grid 1+2, Grid 1+2+3) are similar to the depth of focus for the central target (Grid 1).

Relationship between Peripheral Visual Acuity and Depth of Focus

There is a positive correlation between visual acuity (logMAR) and depth of focus: both visual acuity and depth of focus become poorer in peripheral vision (Figure 5.9b). Green *et al.* developed the following equation to relate depth of focus and visual acuity (their equation 8):[27]

$$\Delta D = 17.45\,\phi/p\ , \tag{5.14}$$

where ΔD is the depth of focus, ϕ is the angular subtense of the minimum resolvable detail (minutes arc), and p is the pupil diameter (mm).

The depth of focus values predicted by Green *et al.* as a function of acuity are much lower than those actually found in this study (Figure 5.9b). This may be because the model of Green *et al.* assumes an aberration-free eye. Also, this study measured depth of focus at the best focus position, and the

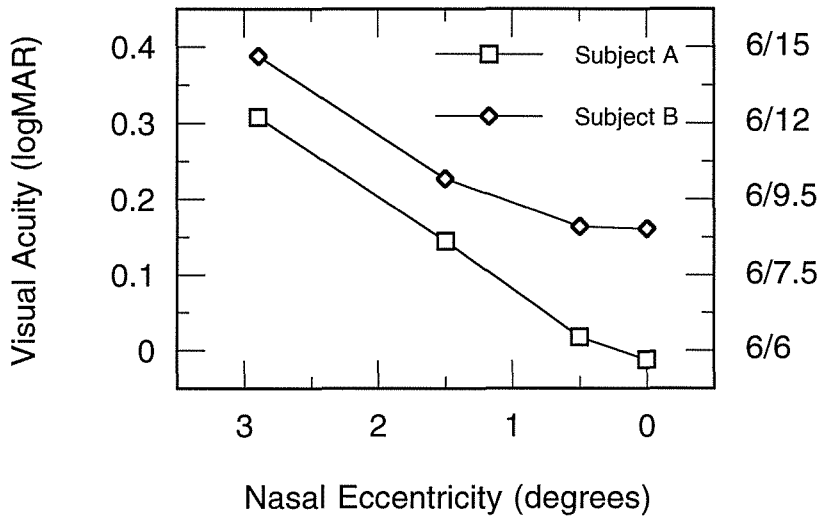


Figure 5.8. Right eye visual acuity in the horizontal nasal meridian as a function of eccentricity for two subjects. LogMAR acuity is shown on the left hand side and conventional Snellen fractions on the right hand side of the plot.

depth of focus is smaller for focus values either side of the best focus position.[20,28]

Peripheral Accommodation

Accommodation gain decreases and phase lag increases for all targets as the temporal frequency of target motion increases (Figure 5.10). Although accommodation appears to be poorer for peripheral targets, the differences in responses between targets are small and not consistent across all temporal frequencies.

The data for the Grid 1, Grid 1+2 and Grid 1+2+3 targets have been replotted in Figure 5.11. Accommodation gain and phase lag are plotted as a function of target outer radius which were 0.5°, 1.5° and 2.9° for Grid 1, Grid 1+2 and Grid 1+2+3 respectively. These plots show that accommodation gain and phase lag in general do not improve as target size is increased. (None of the data sets show a significant linear trend at the 5% level, except the phase lag data for subject A viewing a target moving at 0.02 Hz, which shows a

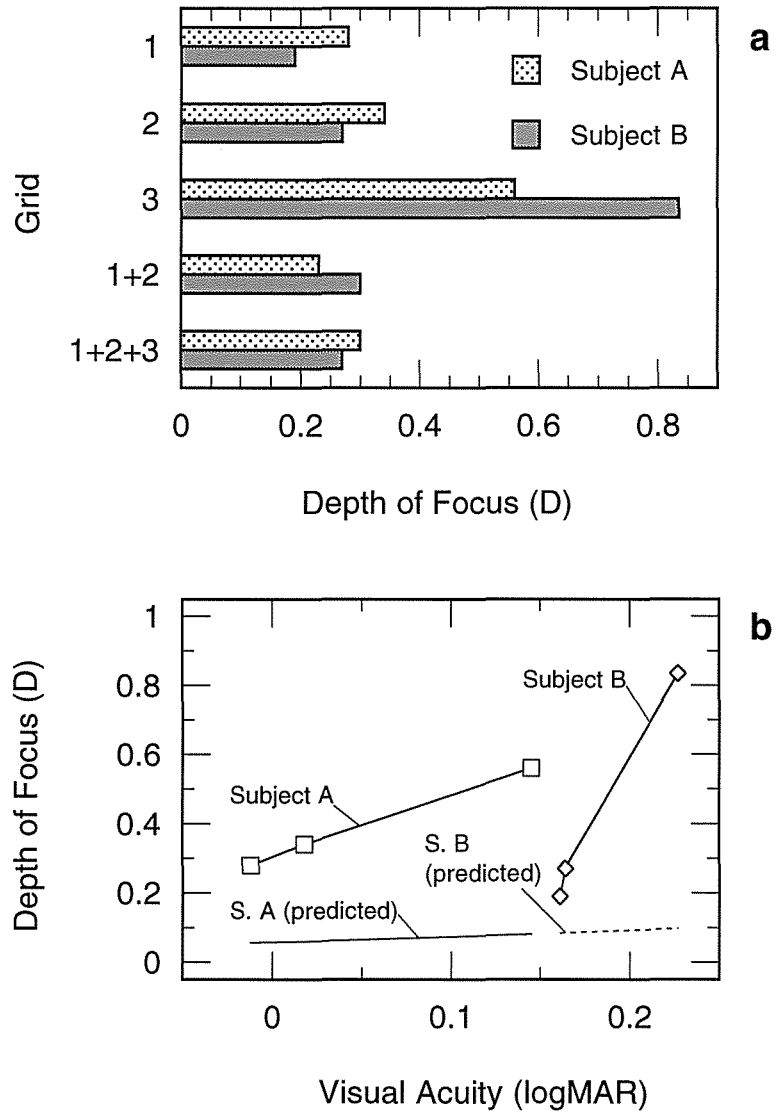


Figure 5.9. Depth of focus for the various grid targets is shown in part (**a**). Part (**b**) plots the depth of focus as a function of visual acuity for both subjects. The depth of focus values predicted by equation 8 of Green *et al.*[27] on the basis of visual acuity are also shown superimposed.

significant (p =0.03) reduction with increasing target size). The range of target sizes in this study are comparable with those of Ciuffreda *et al.*, however these authors found an improvement in steady state accommodation with increasing target size.[6,8]

The peripheral stimulus control model predicts improved gain and phase lag for larger targets; however the experimental data do not show these

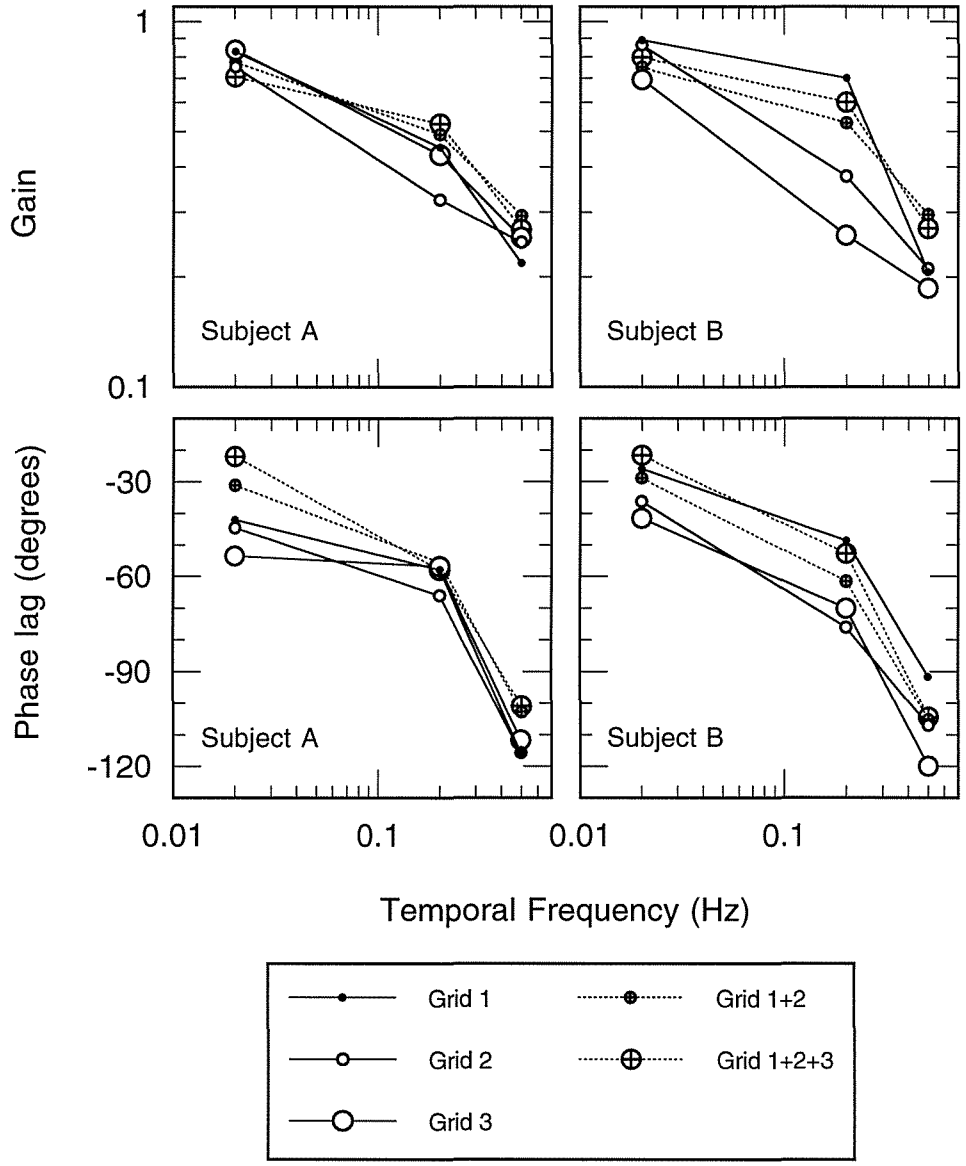


Figure 5.10. Gain and phase lags for various grid targets.

improvements (Figure 5.11). Also, the model predicts that increasing target size will lead to relatively greater improvements in accommodation gain for quickly moving than for slowly moving targets. This effect is also not seen in the experimental data. The modelled response for subject B and a 3° disc shows a high gain probably due to an instability of the model. Subject B's large depth of focus for the Grid 3 target required a high accommodation controller gain (Table 5.2), and the responses were difficult to model with the first order system controller.

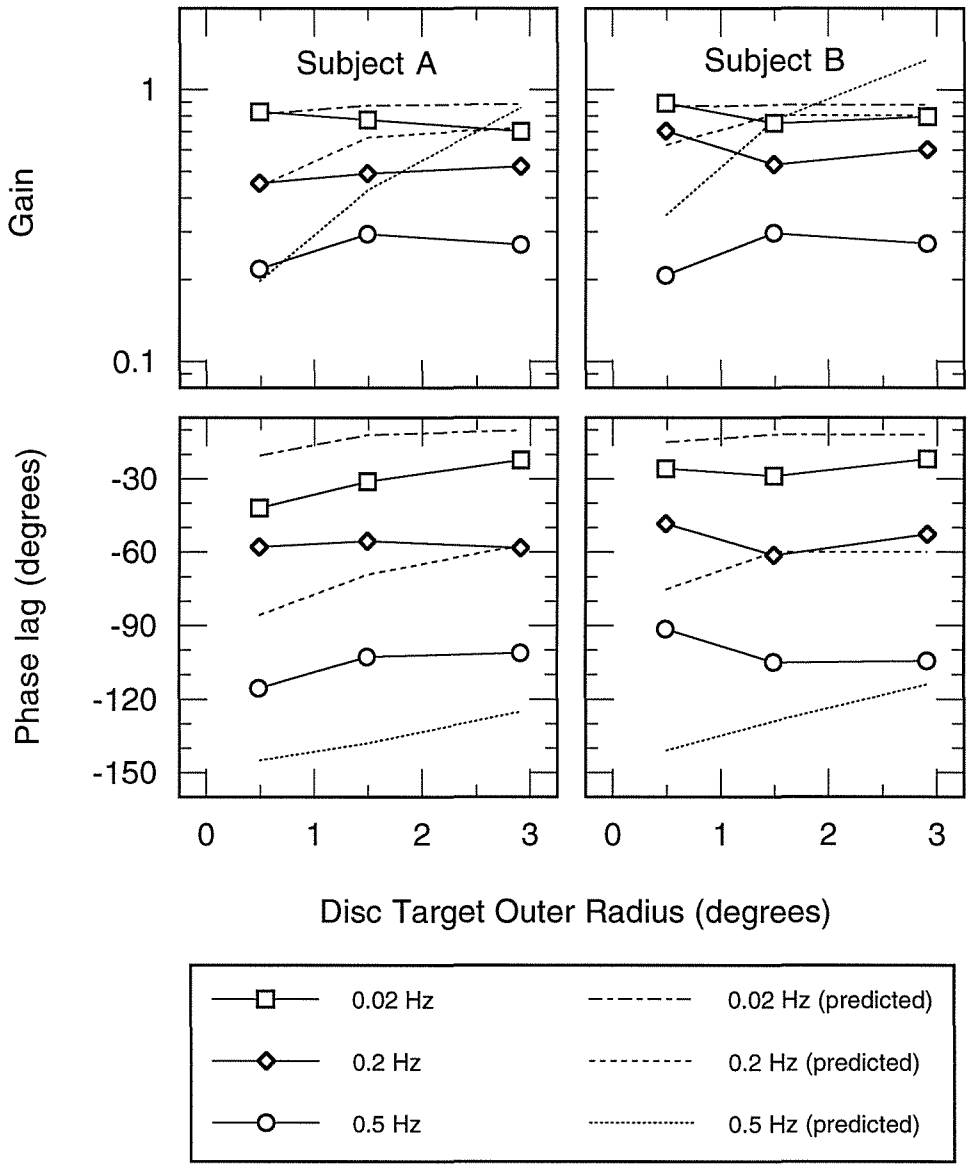


Figure 5.11. Accommodation gain and phase lag for the Grid 1, Grid 1+2 and Grid 1+2+3 targets. The gain and phase lag are plotted as a function of the target outer radius, separately for subjects A and B. The responses predicted by the peripheral accommodation control model are shown superimposed.

The data of Figure 5.10 for Grid 1, Grid 2 and Grid 3 are replotted in Figure 5.12. This graph shows how accommodation performance depends on the eccentricity of peripheral target. Although the detail of the grid targets were not localised at specific eccentricities, the data have been plotted as a function of the inner radius of the target because the target detail closer

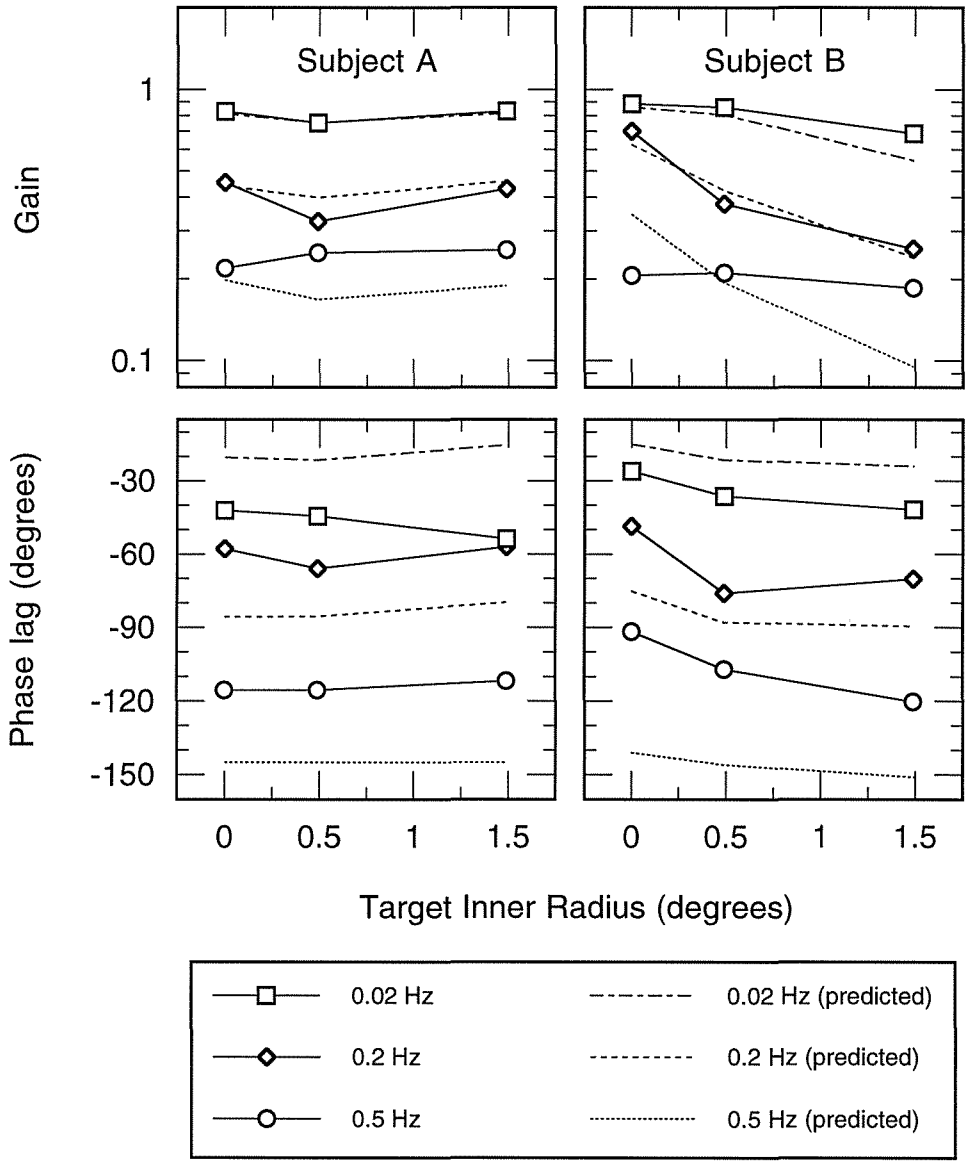


Figure 5.12. Accommodation gain and phase lag for the Grid 1, Grid 2 and Grid 3 targets. The gain and phase lag are plotted as a function of the target inner radius, separately for subjects A and B. Grid 1 is taken to have an inner radius of 0°. The responses predicted by the peripheral accommodation control model are shown superimposed.

to the centre is likely to have a greater influence on accommodation than more peripheral target detail. The accommodation responses of subject A do not appear to alter consistently with target eccentricity, although subject B generally shows poorer responses for the more peripheral targets.

It was originally hypothesised that sinusoidal target motion of a sufficiently high frequency would be too quick to allow subjects to accurately track the target using voluntary trial-and-error focus changes. Thus if subjects focussed for slowly moving peripheral targets but not for quickly moving targets, then this would suggest that they use voluntary accommodation to focus steady peripheral targets. The responses for subject A do not show voluntary accommodation according to this hypothesis (Figure 5.12). This is because the drop off in accommodation gain with temporal frequency does not depend on the eccentricity of the target. Put in another way, accommodation still occurs for quickly moving peripheral targets. Subject B's responses may show voluntary accommodation for peripheral targets. This is because he can focus fairly adequately for slowly moving peripheral targets, but not so well for quickly moving peripheral targets.

Relationship between Peripheral Accommodation and Visual Acuity

Charman[29] hypothesised that the steady state accommodation stimulus–response function slope (m) is related to visual acuity (MAR) by the relationship

$$|m| = 1 - c.(MAR) \; . \qquad (5.15)$$

The data from this study for a target moving at 0.02 Hz (i.e. almost steady) gave values of -0.09 minute^{-1} and +0.79 minute^{-1} for the constant c for subjects A and B respectively. These compare with the mean value of +0.17 minute^{-1} for c obtained by Bullimore and Gilmartin for seven subjects.[30] The values of c obtained in this study are not very reliable due to the small ranges of minimum angle of resolution values over which they were obtained: a range of 0.4 minutes and 0.24 minutes for subjects A and B in this study compared with about 4 minutes in Bullimore and Gilmartin's study.

5.4. Discussion

Does Peripheral Target Detail Assist Accommodation?

The accommodation responses of the two subjects in this study did not improve with larger targets (Figure 5.11). This result shows that large, extended objects are not needed for an accurate accommodation response. Furthermore, these results were found for targets moving both slowly and quickly in depth.

The results of the present study conflict with the data of Ciuffreda *et al.* (over a similar range of target sizes) who found a small improvement in steady state accommodation accuracy for larger targets.[6,8] It is difficult to account for these differences, because Ciuffreda *et al.* provided little experimental detail. It is possible that the differences between the studies may be due to the adequacy of the targets as stimuli to accommodation. However, the estimated gains for 0.5° and 3.0° radius discs in the study of Ciuffreda *et al.* are 0.675 and 0.875 respectively.* This compares to gains for 0.5° and 3.0° radius discs (temporal frequency of 0.02 Hz) in this present study of 0.83–0.89 and 0.69–0.84 respectively. Because there are no definite differences in the gains found in both studies, target adequacy probably would not explain the differences between the two studies. The differences between studies may be due to subject experience: both subjects in this study were highly experienced observers, and it may be that the subjects in the study of Ciuffreda *et al.* were not as experienced. The differences between the findings of Ciuffreda *et al.* and this study suggest the need for further research.

The data of this study also conflict with a dynamic control model of accommodation (Figure 5.7). The model predicts improved performance for larger targets (Figure 5.11). A possible reason for the failure of the control model is that it assumes attention is directed to all parts of the target at the same time. For example, when the subject views the Grid 1 target then both the subject and the model are paying attention to the target. When the

* I estimated steady state gain as (AR - ABIAS)/(AS - ABIAS) where AR is the accommodation response, AS is the accommodative stimulus, and ABIAS is the resting level of accommodation.

subject views the Grid 2 target, the model also 'pays attention' to the Grid 2 target. Note though that when the model 'looks' at a Grid 1+2 target it is 'paying attention' to both the central (Grid 1) and peripheral (Grid 2) part of the target. The subject viewing the Grid 1+2 target may ignore the peripheral (Grid 2) part of the target. Thus the subject would show little improvement in accommodation performance for larger targets, while the model would show an improvement because it 'pays attention' to all parts of the target.

A possible criticism of the control model, which I do not think is important in this particular study, relates to whether a target can be considered spatially as the sum of its parts. For example, both a Grid 1 and a Grid 2 target provide an edge at 0.5° radius: for the Grid 1 target it is an outer edge, and for the Grid 2 target it is an inner edge. However when the Grid 1 and Grid 2 targets are superimposed to give a Grid 1+2 target, this edge disappears (Figure 5.6). These differences would be reflected in the Fourier spectra of the respective targets. However it is unlikely that the eye can perform this *global* sort of Fourier analysis or spatial frequency analysis.[10] Therefore, only changes in spatial detail over small *patches* of the visual field are likely to be of importance. The grid edge provides a wide spectra of spatial detail, although the 4 cycle.degree^{-1} detail next to the edge should still provide a good stimulus to accommodation even if the edge disappears, as it does for the Grid 1+2 and Grid 1+2+3 targets. Mathews *et al.* have shown that accommodation to sinusoidal target motion (with an amplitude of a similar magnitude to this study) is most accurate for mid spatial frequency detail (3–5 cycles.degree^{-1}).[15] Taking into account the reduced acuity in peripheral vision (by way of the cortical magnification factor[12]), the 4 cycle.degree^{-1} detail at peripheral locations should have still provided adequate detail to the accommodation system. For example, the 4 cycle.degree^{-1} detail at eccentricities of 0.5° and 1.5° has the same cortical representation as spatial frequency detail of 4.7 cycle.degree^{-1} and 6 cycle.degree^{-1} at the fovea respectively. The value of an edge is that it provides relatively stronger low spatial frequency information than the 4 cycle.degree^{-1} detail when the target is defocused. This low spatial frequency

detail might have been useful to the accommodation system for larger amplitudes of target motion.

Dynamic Responses to Peripheral Targets

This study is the first to show dynamic responses of accommodation for sinusoidally moving peripheral targets (Figure 5.12). However the roles of voluntary and reflex accommodation in these dynamic responses is uncertain. It was originally hypothesised that sinusoidal target motion of a sufficiently high frequency would be too quick to allow subjects to accurately track the target using voluntary trial-and-error focus changes. Thus if subjects focussed for slowly moving peripheral targets but not for quickly moving targets, then this would suggest that they use voluntary accommodation to focus steady peripheral targets.

One subject's (subject A) responses do not show voluntary accommodation to peripheral targets according to this hypothesis, while the other subject's (subject B) responses do show evidence for voluntary control (Figure 5.12). It may be that these findings represent individual differences in peripheral accommodation ability.[3]

Although the faster target motion in this study (0.2 Hz and 0.5 Hz) may have been predictable, the targets were probably moving too quickly for voluntary trial-and-error hunting movements. This fits in with subject reports that they generally did not know what their accommodation was doing when looking at the faster moving targets. However subject B was sometimes aware that he was better 'in sync' with the target motion in some trials.

Subjects may have been looking over to the peripheral target detail instead of fixating centrally. Unfortunately there was no way to monitor eye movements in the present apparatus although some comments can be made on the role of incorrect fixation on the results. I assume that the experienced subjects in this study did not always look in the wrong direction, although it is likely that they sometimes were unable to maintain correct fixation. These short errors of fixation may have aided the slowly moving 0.02 Hz target due

to tonic adaptation. For quickly moving targets (0.2 Hz and 0.5 Hz) short errors of fixation may have lead to momentary improvements in accommodation accuracy, and this would be detected by the Fast Fourier Transform. Therefore eye movements may have affected the results in this study, although the magnitude of this effect is not known. It should be noted though that small eye movements are necessary for accommodation and to prevent perceptual fading,[31,32] so the researcher cannot unrealistically expect to determine accommodation performance in discrete retinal areas smaller than the magnitude of these eye movements.

5.5. Summary

1. Contrary to the study of Ciuffreda *et al.*, this study found that accommodation does not become more accurate for larger targets.[6,8] Accommodation gain and phase lag for dynamic targets (0.02 Hz, 0.2 Hz, 0.5 Hz) do not improve as target radius is increased from 0.5° to 2.9°. This seems to contradict the view that there is pooling of central and near peripheral retinal cone signals to the higher accommodation control centres.
2. A dynamic control model of the accommodation response to peripheral and extended targets performs poorly at predicting responses to extended targets. The model predicts improved accommodation performance for larger targets, however this was not found experimentally in this study. The failure of the model may be due to its assumption that subjects attend equally to both the central and peripheral detail of a target, when in reality they may selectively attend to the central detail.
3. This is the first study to demonstrate dynamic accommodation responses to sinusoidal peripheral target motion. With respect to the roles of 'reflex' and voluntary accommodation in accommodation to peripheral targets, one subject showed evidence of voluntary accommodation for peripheral targets while the other did not.

References

1. Whiteside, T.C.D. *The Problems of Vision in Flight at High Altitude.* London: Butterworths, 1957.
2. Phillips, S.R. *Ocular Neurological Control Systems: Accommodation and the Near Response Triad.* PhD Thesis. Berkeley: University of California, 1974. pp. 123–152; 289–339.
3. Semmlow, J.L. and T. Tinor. Accommodative convergence response to off-foveal retinal images. *J. Opt. Soc. Am.* 1978, **68**(11), 1497–1501.
4. Bullimore, M.A. and B. Gilmartin. The influence of retinal areas stimulated on the accommodative response. *In:* A. Fiorentini, D.L. Guyton and I.M. Siegel eds. *Advances in Diagnostic Visual Optics.* Berlin: Springer-Verlag, 1987. pp. 181–185.
5. Gu, Y. and G.E. Legge. Accommodation to stimuli in peripheral vision. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1987, **4**(8), 1681–1687.
6. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction.* Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
7. Hung, G.K. and K.J. Ciuffreda. Accommodative responses to eccentric and laterally-oscillating targets. *Ophthalmic Physiol. Opt.* 1992, **12**, 361–364.
8. Ciuffreda, K.J., N.A. McBrien and S.K. Fisher. Accommodation with and without foveal contribution [Abstract]. *Optom. Vision Sci., Suppl.* 1989, **66**(10), 108.
9. Schwartz, E.L. Computational anatomy and functional architecture of striate cortex: a spatial mapping approach to perceptual coding. *Vision Res.* 1980, **20**, 645–669.
10. Robson, J.G. Receptive fields: neural representation of the spatial and intensive attributes of the visual image. *In:* E.C. Carterette and M.P. Friedman eds. *Handbook of Perception.* New York: Academic, 1975. vol. 5. pp. 81–112.
11. De Valois, R.L. and K.K. De Valois. Spatial vision. *Ann. Rev. Psychol.* 1980, **31**, 309–341.
12. Rovamo, J. and V. Virsu. An estimation and application of the human cortical magnification factor. *Exp. Brain Res.* 1979, **37**, 495–510.
13. van der Wildt, G.J., M.A. Bouman and J. van de Kraats. The effect of anticipation on the transfer function of the human lens system. *Opt. Acta (Lond.).* 1974, **21**(11), 843–860.
14. Owens, D.A. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980, **20**, 159–167.
15. Mathews, S. and P.B. Kruger. Spatiotemporal transfer function of human accommodation. *Vision Res.* 1994, **34**, 1965–1980.
16. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 34–35; 252–253.
17. Bailey, I.L. and J.E. Lovie. New design principles for visual acuity letter charts. *Am. J. Optom. Physiol. Opt.* 1976, **53**, 740–745.
18. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin.* 1972, **77**(1), 54–64.
19. Campbell, F.W. and G. Westheimer. Sensitivity of the eye to differences in focus [Abstract]. *Journal of Physiology. Supplementum.* 1958, **143**, 18P.
20. Walsh, G. and W.N. Charman. Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Res.* 1988, **28**(11), 1207–1221.
21. Microsoft Corporation. *Excel®.* 3.5 inch H.D. floppy disc. Version 4.0. Redmond, West Virginia: Microsoft Corporation, 1992.

22. Shirachi, D., J. Liu, M. Lee, J. Jang, J. Wong and L.W. Stark. Accommodation dynamics. 1. Range nonlinearity. *Am. J. Optom. Physiol. Opt.* 1978, **55**(9), 631–641.
23. Wertheim, T. Über die indirekte Sehschärfe. *Z. Psychol. Physiol. Sinnesorgane.* 1894, **7**, 172–187.
24. Low, F.N. Peripheral visual acuity. *A. M. A. Arch. Ophthalmol.* 1951, **45**, 80–99.
25. Millodot, M. Foveal and extra-foveal acuity with and without stabilized retinal images. *Br. J. Physiol. Opt.* 1966, **23**(2), 75–106.
26. Le Grand, Y. *Form and Space Vision.* Revised ed. Bloomingtown: Indiana University Press, 1967. pp. 126–145.
27. Green, D.G., M.K. Powers and M.S. Banks. Depth of focus, eye size and visual acuity. *Vision Res.* 1980, **20**, 827–835.
28. Campbell, F.W. The depth of field of the human eye. *Opt. Acta (Paris).* 1957, **4**(4), 157–164.
29. Charman, W.N. Static accommodation and the minimum angle of resolution. *Am. J. Optom. Physiol. Opt.* 1986, **63**(11), 915–921.
30. Bullimore, M.A. and B. Gilmartin. Retinal eccentricity and the accommodative response. *Am. J. Optom. Physiol. Opt.* 1987, **64**(8), 644–645.
31. Fincham, E.F. The accommodation reflex and its stimulus. *Br. J. Ophthalmol.* 1951, **35**, 381–393.
32. Kotulak, J.C. and C.M. Schor. The accommodative response to subthreshold blur and perceptual fading during the Troxler phenomenon. *Perception.* 1986, **15**, 7–15.

Chapter 6

Voluntary Accommodation and the Mandelbaum Effect

6.1. Introduction

In this study I test the hypothesis that people use memorised voluntary accommodation to overcome the Mandelbaum effect. *Memorised voluntary accommodation* is the ability to set accommodation for a memorised target distance even though the objects at that distance are hidden by a conflicting target. The *Mandelbaum effect* is the involuntary shift of accommodation towards a conflicting target away from the normal response for an attended target. I hypothesise that people overcome the Mandelbaum effect by voluntarily setting their focus to the memorised or known distance of the desired target. Consequently, people with good memorised voluntary accommodation should easily overcome the Mandelbaum effect, while those

with poor memorised voluntary accommodation should have difficulty overcoming the Mandelbaum effect.

The Mandelbaum Effect

In his paper 'An Accommodation Phenomenon', Mandelbaum described the difficulty he had when trying to focus distant buildings through the window screen of his hospital room.[1]

Later on, when investigating this phenomenon on the screen enclosed porch of his summer cottage, Mandelbaum's subjects were also unable to prevent themselves focusing to the intervening screen. Mandelbaum concluded:

> The accommodation act has not only been clearly removed from the conscious level, but so completely that conscious efforts to remedy the situation failed.[1]

Thus it appeared that voluntary ability was unable to overcome this unwanted response to a conflicting target. However, while resident at the Bellevue Hospital, Mandelbaum noted that not everyone could observe the phenomenon. While these persons may simply have been inobservant, it is also possible that they were able to overcome the phenomenon.

Suggestions that Voluntary Accommodation May Influence the Mandelbaum Effect

There are suggestions in the literature that voluntary accommodation plays a role in the Mandelbaum effect (see section 1.8.1.4).

Voluntary accommodation ability varies within the population,[2-4] as does the Mandelbaum effect.[5] It may be that people with poorer voluntary accommodation show a larger Mandelbaum effect. It is possible that people learn to improve their voluntary accommodation with practice and then use this voluntary ability to reduce the Mandelbaum effect. Numerous studies have shown that training can improve voluntary accommodation,[3,6-11] and

one subject in Owens' study showed smaller Mandelbaum effect values after practice.[5]

The observations I have made from Owens' study[5] seem to contradict Mandelbaum's[1] conclusion that voluntary accommodation cannot overcome the response to a conflicting target. However, Mandelbaum did not measure accommodation in his study, so he would not have detected differences in accommodation responses between subjects. Nevertheless, both Mandelbaum's and Owens' studies show that even the best performing subjects cannot completely overcome the response to a conflicting target.

Other Research

Roscoe and Couchman[12] studied whether voluntary accommodation training could improve distance Snellen acuity when viewing through an intervening screen. This 'Mandelbaum compensation test' was administered both before and after voluntary accommodation training. The interposed window screen significantly reduced acuity, and there was no improvement in acuity after voluntary accommodation training. A simple explanation is that subjects were not able to overcome the Mandelbaum effect even after voluntary training. However, the window screen may have reduced Snellen acuity mainly by obscuring the details of the letters. Even if subjects were accommodating more carefully to the distant target, they would not have made any gains in acuity because the screen was obscuring the letters. Unfortunately Roscoe and Couchman did not measure accommodation in their study.

Types of Voluntary Accommodation

Voluntary accommodation describes a number of related accommodation actions, but it is uncertain which of these may be used to overcome the Mandelbaum effect. These various forms of voluntary accommodation range from relatively passive responses through to active responses that can only be achieved with a good deal of practice (see section 1.2.5 for a comprehensive review). I chose to investigate memorised voluntary

accommodation in this study because it is possible to construct targets (see later) to directly test the hypothesis that people use this particular form of voluntary accommodation to overcome the Mandelbaum effect.

When we change our attention from one object to another then accommodation follows 'reflexly', usually without our conscious knowledge. However, a voluntary change in attention preceded the accommodation response. Furthermore, Phillips demonstrated that the early response to a step change in target vergence is probably voluntary in nature: he called this response a *normal volitional accommodative response.*[13] It is possible that subjects overcome the Mandelbaum effect by attending to and concentrating on the desired target: the same as when concentrating on a single target.

A more active voluntary process occurs when subjects exert voluntary effort to hunt for the best focus position of a target.[14-17] They alter their focus closer and further by a trial-and-error method to find the best focus position. Although strenuous, the task is similar to normal everyday situations because the aim is to see the target clearly. If there are two conflicting targets, a subject may use this hunting procedure to focus on the desired target.

As a more difficult task, subjects in some studies have been required to make voluntary excursions of focus away from a target viewed in normal closed-loop conditions. Subjects were permitted to respond by any magnitude,[2] or by any magnitude in any direction.[10,13,18,19] In one study, naive subjects were instructed to imagine a pinpoint target 'as near as possible' or 'as far away as possible'.[20]

A difficult voluntary task is to maintain accommodation at a specified and remembered position even though a conflicting target is present.[6,10,12] The subject may use proprioception or the blurring of the conflicting target as cues, but they must contend with the accommodation stimulus provided by the conflicting target. Subjects may overcome the Mandelbaum effect by locking on to the remembered focus level of the desired target, and thus they would not need the blur cues provided by the desired target. I called this form of voluntary accommodation *memorised voluntary accommodation* to

avoid confusion with other forms of voluntary accommodation, and because subjects use voluntary effort to focus for a memorised target position.

6.2. Methods

Experimental Design

To test the hypothesis that people use memorised voluntary accommodation to overcome the Mandelbaum effect I measured the accommodation responses of 16 subjects with three different target configurations (Figure 6.1). In the first Control Condition I measured the subject's response to a distant letter target (Figure 6.1a). In the two Mandelbaum Effect Conditions I measured the subject's response to the same distant target but with a mesh target superimposed either close to their individual dark focus or at 50 cm (Figure 6.1b). The subject viewed the distant target through the mesh target. This condition is a test of the subject's susceptibility to the Mandelbaum effect. In the two Voluntary Accommodation Conditions I measured the subject's accommodation response while viewing an opaque mesh placed at the same distances as the mesh targets of the Mandelbaum Effect Conditions (Figure 6.1c). In the Voluntary Accommodation Conditions the opaque mesh completely obscured the distant target, and the subject's task was to focus to the distance of the distant letter target even though it could not be seen, and even though there was a mesh target at a closer distance. This is a test of the subject's memorised voluntary accommodation ability.

It is important to note that the main difference between the Mandelbaum Effect Conditions and the Voluntary Accommodation Conditions (apart from subject instructions) is the background of the mesh target. In the Mandelbaum Effect Conditions the mesh has a *transparent* background and the subject views the distant target through the mesh: this is a test for susceptibility to the Mandelbaum effect. In the Voluntary Accommodation Conditions the mesh has an *opaque* background and the subject has to focus

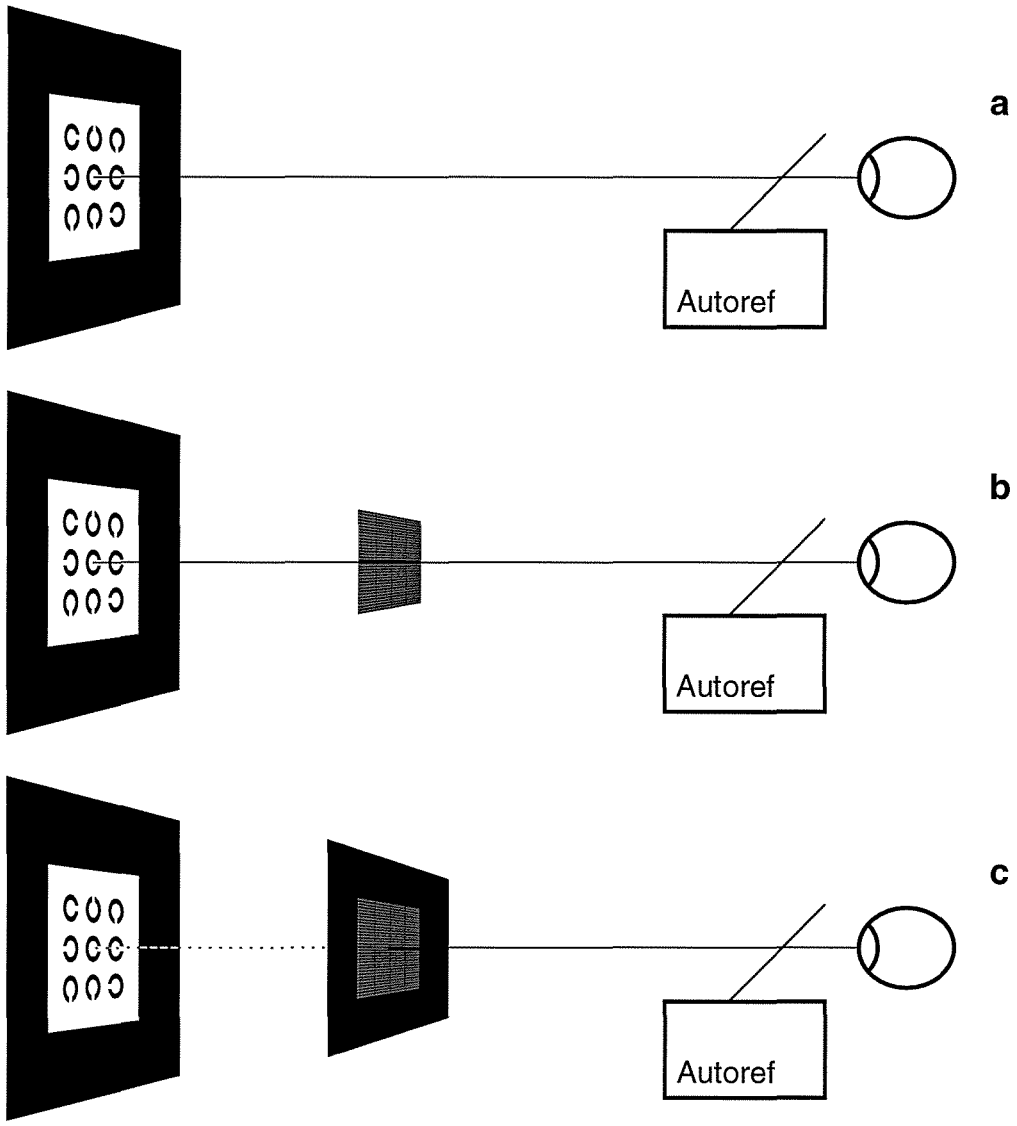


Figure 6.1. Schematic diagram of the various target conditions. In the Control Condition (**a**) the subject views the distant Landolt C target directly at a distance of 3.8 m. In the Mandelbaum Effect Conditions (**b**) the subject views the distant target with a mesh superimposed. In the Voluntary Ability Conditions (**c**) the subject views the opaque mesh target while trying to focus to the distant target. Note that in this last condition (**c**), the opaque mesh completely obscures the distant target from the subject's view. (Targets and apparatus are described later.)

for the memorised distance of the distant target even though the distant target can not be seen: this is a test of memorised voluntary accommodation.

Now the hypothesis of this study is that people use memorised voluntary accommodation to overcome the Mandelbaum effect. If the hypothesis is correct, then for an individual subject the accommodation responses should be the same in the Mandelbaum and Voluntary conditions. This is because the subject uses the same voluntary process in both situations: the subject uses memorised voluntary accommodation to focus away from the mesh in the Mandelbaum Condition, and uses memorised voluntary accommodation to focus away from the mesh in the Voluntary Condition. In both conditions the subject ignores the visual cues provided by the mesh and the distant target, and focuses to the remembered position of the distant target.

The hypothesis predicts that subjects with good memorised voluntary accommodation focus close to the distant target in both the Mandelbaum and the Voluntary Conditions. Subjects with poor memorised voluntary accommodation focus somewhere away from the distant target in both the Mandelbaum and Voluntary Conditions. Therefore a plot of Mandelbaum Condition responses as a function of Voluntary Condition responses should have a slope of +1 and an intercept of zero. I used regression analysis to test whether these predictions were correct.

Subjects

Nineteen subjects participated in the study, and of these, three were excluded from the analysis. One subject misinterpreted the instructions. A second subject was wearing her habitual contact lens correction which caused spurious cylindrical values in the Autoref readings (see below for a description of the Autoref optometer). A third subject's pupils were too small to obtain consistent readings with the Autoref optometer. The sixteen remaining subjects were aged between 16 and 39 years, and had right eye subjective amplitudes of accommodation (4.2 D to 12.5 D with a Rodenstock hand optometer) sufficient for the tasks involved in the experiment. Visual acuities in the right eye ranged between 6/3 and $6/6^{+2}$. Right eye best sphere refractive errors ranged between -2.1 DS and +1.0 DS, and cylindrical components of the refractive error were less than or equal to 0.50 DC. I

attempted to recruit subjects with a wide a range of experience in accommodation experiments and, presumably, a wide range of voluntary accommodation ability. Of the sixteen subjects, 5 had no previous experience in accommodation experiments, 9 had some experience, and 2 had extensive experience. Subjects were academic and research staff of the Q.U.T. School of Optometry, undergraduate and postgraduate optometry students of the School, and members of the public.

Apparatus

OPTOMETER

I measured accommodation with a Canon Autoref R-1 infra-red optometer, operating in its standard mode (see Appendix A).[21] This optometer provides an open field of view for the presentation of targets in real space. The refraction readings provided by the Autoref were calibrated against subjective refraction in separate experiments (see section A.2). Calibration equations were used to modify all later experimental Autoref readings. Pupil size measurements were made from a video monitor connected to the Autoref. I used a calibration equation to convert monitor image size to actual pupil size.

TARGETS

Various targets were constructed for presentation to the subjects in real space. The distant target was a block of nine black on white 6/60 Snellen equivalent Landolt C's (Figure 6.2a).[22] The Landolt C was chosen because its oblique line elements can never be completely obscured by the vertical and horizontal elements of the superimposed mesh. The nine Landolt C's were grouped on a white square block having a side of 5°. The Landolt C's were separated from each other by 25 minutes arc, and the outer C's were 50 minutes arc from the edge of the block. This white 5° block was further centred in a square black surround field 9.6° square. This distant target was viewed at a distance of 3.8 m. The letters had an estimated Michelson contrast[23] of 58%. The white background of the distant target had a

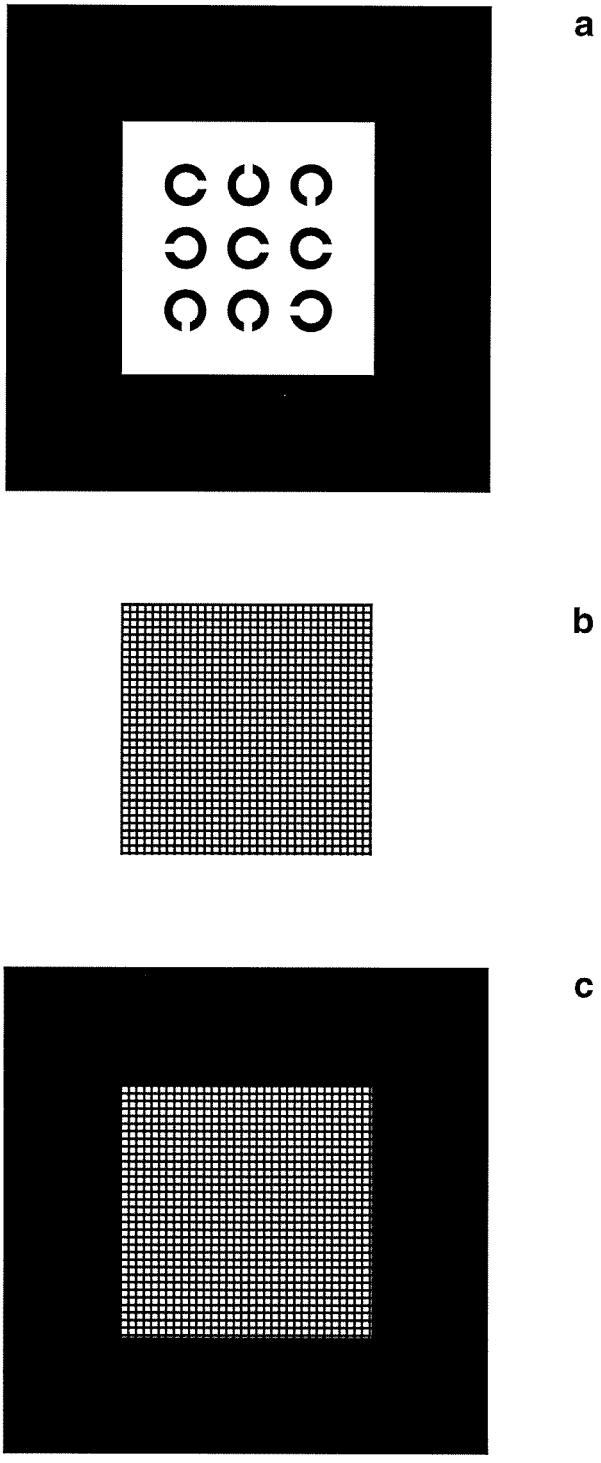


Figure 6.2. (**a**) The distant Landolt C target, (**b**) the mesh on a transparent background, and (**c**) the mesh on an opaque background. The angular dimensions are drawn to scale. See the text for details.

luminance in the range 55–68 cd.m^{-2}, sufficient for an accurate accommodation response.[24]

The mesh targets used in the Mandelbaum Condition (Figure 6.1b) were printed on transparent sheets (Figure 6.2b). The mesh consisted of black vertical and horizontal crossing limbs. The limbs were 3 minutes arc wide separated by 6 minute arc gaps. The mesh pattern was 5° square, and completely overlapped all the Landolt C's of the distant target. The grating period of 9 minute arc corresponds to a spatial frequency of 6.7 cycles.degree^{-1}. For this spatial frequency, higher order harmonic components are unlikely to have contributed to the accommodation response,[25,26] and the fundamental frequency should have provided a good stimulus to accommodation.[27] The design of the grating meant that regardless of the subject's direction of gaze, grating detail was always present no greater than 3 minutes of arc from the fixation point. There is controversy over how much of the visual field is involved in accommodation (see section 1.5.4), but all studies would agree that accommodation can be activated by a target at an eccentricity of 3 minutes arc. Thus, subjects were not able to ignore the conflicting mesh target by adopting an eccentric direction of gaze. A number of individual mesh targets were constructed to have equal angular dimensions when placed at dioptric distances of 0.5 D to 2 D, in 0.25 D increments. Estimated Michelson mesh contrasts ranged between 40% and 61%. Room lighting was placed to prevent the subject from seeing reflections from the surface of the plastic transparency.

The opaque mesh targets used in the Voluntary condition (Figure 6.1c) had identical dimensions to the meshes used in the Mandelbaum condition, except that they were printed on opaque white card (Figure 6.2c). The mesh pattern was centred on a black background 9.6° square. The black surround was needed to prevent subjects obtaining a view of the distant block of C's if the two targets were not perfectly aligned. It could be argued that the texture of the black surround field aided accommodation by providing extra peripheral detail when compared to the mesh on a transparent background (which had no surround field). However, both the opaque and transparent

background meshes had good central detail, and in this situation peripheral detail does not aid accommodation (see Chapter 5). The space-averaged luminance of the opaque meshes varied in the ranges 28–75 cd.m^{-2} and 33–48 cd.m^{-2} for the meshes placed close to the individual dark focus, and at 50 cm respectively. Estimated Michelson mesh contrasts ranged between 53% and 88%.

Although the various targets had different luminances and contrasts, accommodation is robust over the range of luminances[24] and contrasts[13,28] involved in this study.

Procedure

PRELIMINARY TESTS

I performed a subjective refraction for each subject's right eye using a criterion of 'maximum plus' for best acuity, and recorded visual acuity with this correction. The subjects wore ophthalmic trial lenses close in power to their subjective refraction throughout the experiment. I usually did not correct cylindrical components of 0.25 DC, and two subjects' cylindrical components of 0.50 DC were inadvertently left uncorrected. The trial lenses worn by subjects altered both the accommodation stimulus levels of the targets and the apparent refractive error of the eye seen by the Autoref optometer. I corrected nominal stimulus and response levels based on the subject's refractive error, the trial lens in place, and the trial lens vertex distance (see section E.2).

MAIN TESTS

Right eye monocular viewing was used throughout the experiment, and the subject's left eye was patched.

I first made pre-task measurements of the subject's dark focus. The subject sat in the completely darkened experimental room for 5 minutes to allow any possible tonic adaptation effects to subside.[13,29] Subjects were aware of the room length before dark adapting, and this had the potential to contaminate the dark focus level.[4,30] However the 3.8 m length should have

been long enough to prevent proximal accommodation from contaminating the dark focus measure.[31] Two dim peripherally located eye-front illuminating lamps were used intermittently to align the eye (see section A.1). After 5 minutes of dark adaptation I instructed the subject to 'look straight ahead at the end of the room', and then took several readings of refractive error from the subject's right eye using the Autoref. (The room was still dark when I took the readings). Although the subject instruction may have affected the dark focus values, the instruction was necessary to stabilise gaze as much as possible.

I then measured accommodation responses in three different stimulus conditions, presented in counterbalanced order for a total of two trials of each condition.[32] The three conditions were:

1. Control condition. The subject viewed a block of 6/60 Landolt C's at a distance of 3.8 m (Figure 6.1a);
2. Mandelbaum effect condition with mesh close to the dark focus. The subject viewed the Landolt C's of (1) but through a Mesh superimposed close to the estimated individual dark focus value (Figure 6.1b);
3. Mandelbaum effect condition with mesh at 50 cm. The subject viewed the Landolt C's of (1) but through a Mesh superimposed at 50 cm (Figure 6.1b).

Note that one trial of each condition was first performed to familiarise the subject with the experiment, followed by a second trial of each condition, to give a total of 6 trials. I used two mesh distances in the study: the individual dark focus level, and 50 cm. According to Owens, a mesh placed at the individual dark focus induces the greatest Mandelbaum effect.[5] I also included a fixed distance of 50 cm to simulate common situations such as viewing through an automobile or aircraft windshields.

Before starting the 6 trials I gave the subjects this instruction:

> You must keep your head very still while measurements are being taken. You should look at the middle C on the wall and view it naturally, the same as you would when normally reading a book or sign at the same distance.

I chose this instruction to bias the subjects as little as possible from their normal responses in similar situations (see Chapter 3). The instruction also specifically required the subject to remain still because Mandelbaum originally noted that head movements could be used to overcome the undesired response to an intervening mesh.[1] Any head movements were readily visible to the experimenter while viewing the Autoref video monitor. Finally, and importantly, the instruction gave the subject the definite task of viewing the distant letter C. In other studies of the Mandelbaum effect the subjects have not been given the definite task of viewing a particular target.[5,33,34]

Immediately after these 6 trials, I made estimates of the subject's memorised voluntary accommodation. I measured accommodation responses in two conditions, presented in counterbalanced[32] order:

4. Voluntary accommodation condition with opaque mesh close to the individual dark focus. The subject viewed the opaque mesh which was placed close to the estimated individual dark focus value (Figure 6.1c);
5. Voluntary accommodation condition with opaque mesh at 50 cm. The subject viewed the opaque mesh which was placed at 50 cm (Figure 6.1c).

Before taking measurements in these two conditions the subject was encouraged to obtain a good view of the room and the distance of the Landolt C target. I then instructed the subjects:

> Look at the centre of the mesh pattern, but ignore the mesh pattern. Imagine you are looking at the letter C on the wall behind the mesh pattern. Focus your eyes to the distance of the letter C, the same as you would when normally focusing on the letter C.

I took twenty readings of accommodation with the Autoref at each trial in the various conditions. I measured horizontal pupil diameters at the start of each trial, and these varied in the range 3.6–7.6 mm. At the end of each trial I asked the subjects the following questions:

1. How did the target appear? Was it blurred or clear?
2. What were you trying to do while looking at the target?

At the end of the experimental session I measured the subject's dark focus in the same way that I had measured it at the start of the session.

Analysis

CALCULATION OF ACTUAL ACCOMMODATION STIMULUS AND RESPONSE LEVELS

Calculation of Ocular Refraction. The subject's ocular refraction was calculated from the measured spectacle refraction, the trial lens vertex distance, and the test chart distance (see section E.2).

Calculation of the Stimulus to Accommodation. The stimulus to accommodation was calculated from the target distance, the subject's ocular refraction, the trial lens power in place, and the trial lens vertex distance (see section E.3).

Calculation of the Response of Accommodation. The accommodation response was calculated from the Autoref readings, from calibration equations for the Autoref, the subject's ocular refraction, the trial lens power in place, and the trial lens vertex distance (see section E.3).

CALCULATION OF REGRESSION ANALYSIS PARAMETERS

The hypothesis of this study is that people use memorised voluntary accommodation to overcome the Mandelbaum effect. If this hypothesis is correct than a plot of the 'Mandelbaum effect' as a function of 'voluntary ability' should have a slope of 1 and a zero intercept.

As a measure of the *Mandelbaum effect* I subtracted the median response when viewing the C target alone from the median response when viewing the C target with mesh interposed, that is,

$$ME_{df} = AR_{cmdf} - AR_c \ , \tag{6.1}$$

and

$$ME_{50} = AR_{cm50} - AR_c \ , \tag{6.2}$$

where:

ME_{df} is the Mandelbaum effect when the mesh was placed close to the individual dark focus level;

ME_{50} is the Mandelbaum effect when the mesh was placed at 50 cm;

AR_{cmdf} is the median accommodation response in the second trial when the C target was viewed with a mesh interposed close to the individual dark focus level;

AR_{cm50} is the median accommodation response in the second trial when the C target was viewed with a mesh interposed at 50 cm;

AR_c is the median accommodation response in the second trial when the C target was viewed alone.

A few points are important to note. Firstly, the Mandelbaum effect is not simply the accommodation response when viewing the distant target through the mesh: it is the *change* in accommodation induced by the mesh. Secondly, the median accommodation responses were used because outliers appeared in some trials and these may have biased calculated mean responses. Finally, only data from the respective second trials of conditions 1 – 3 were used in the analysis. This was to allow a better comparison with the two voluntary accommodation conditions (conditions 4, 5) that followed directly after the second trials of conditions 1 – 3.

As a measure of the error of voluntary accommodation (the *voluntary error*) I subtracted the median response when viewing the C target alone from the median response when attempting to voluntarily focus to the hidden C target, that is,

$$VE_{df} = AR_{vdf} - AR_c \tag{6.3}$$

and

$$VE_{50} = AR_{v50} - AR_c\ , \tag{6.4}$$

where:

VE_{df} is the voluntary error when the opaque mesh was placed close to the individual dark focus level;

VE_{50} is the voluntary error when the mesh was placed at 50 cm;

AR_{vdf} is the median accommodation response when attempting to focus for the hidden C target, with an opaque mesh in place close to the individual dark focus level;

AR_{v50} is the median accommodation response when attempting to focus for the hidden C target, with an opaque mesh in place at 50 cm;

AR_c is the median accommodation response in the second trial when the C target was viewed alone.

It is important to note the significance of the voluntary error variables (VE_{df}, VE_{50}). The voluntary error is the difference between the response when attempting memorised voluntary accommodation, and the response to the C target by itself. A subject with a small value for the voluntary error can focus close to their normal distant response level even though the distant target is hidden. Thus a small value of the voluntary error indicates good memorised voluntary accommodation, while a large value of the voluntary error indicates poor memorised voluntary accommodation. This way of describing voluntary ability corresponds to the values of the Mandelbaum effect where a small value of the Mandelbaum effect also indicates good control of accommodation, and a large value indicates poor control of accommodation.

REGRESSION AND CORRELATION TECHNIQUES

I calculated Pearson correlation coefficients between the Mandelbaum effect and voluntary error for the two mesh distances (dark focus and 50 cm) separately. A potential confounding factor in these correlations is that the dioptric distance between the C target and the mesh varied from subject to subject. For example, the C target and the mesh were close together if a subject had a low dark focus level, but widely separated if the subject had a high dark focus level. To account for this factor I used the method of partial correlations (see section C.1).[35] Using partial correlations it is possible to calculate the correlation between the Mandelbaum effect and the voluntary error, but with the effects of C target – mesh target spacing partialled out.

I used principal axis regression[36] to calculate best fitting lines to the plots of Mandelbaum effect as a function of voluntary error. I also calculated approximate confidence intervals for the slopes of these lines.[36] Principal axis regression is used instead of linear regression because there is no true independent variable, and because the correlation coefficients are not high.

VARIABILITY OF THE ACCOMMODATION RESPONSES

It is possible that accommodation becomes more variable in the Mandelbaum Effect task or in the Voluntary Accommodation task. As a formal test, the *accommodation range* was used as a parameter, and the effect of the various trial conditions was investigated with a non-parametric test: the Friedman test (see section C.2).[37] The accommodation range is the difference between the maximum and minimum accommodation values recorded during a trial.

6.3. Results

Individual Subjects

Individuals varied widely in their voluntary accommodation ability, although most performed well in overcoming the Mandelbaum effect. Three

subjects responses will serve to illustrate some of these differences (Figures 6.3 through 6.5).

Subject E demonstrated very little Mandelbaum effect: his responses to the C were unaffected by the interposition of the mesh either close to his dark focus or at 50 cm (Figure 6.3). When viewing the opaque mesh he was able to use voluntary accommodation to place his focus at almost the same level as when viewing the distant target directly.

Subject L was not affected by the mesh when it was placed close to her dark focus, though she did suffer a Mandelbaum effect when the mesh was placed at 50 cm (Figure 6.4). Her voluntary response was higher than when viewing the distant C through the mesh. This suggests she was using different accommodation strategies in the two situations.

Finally, Subject N showed no observable Mandelbaum effect, but in the test of voluntary accommodation placed his focus beyond that when he was viewing the distant C target alone (Figure 6.5).

It should be noted that the Figures 6.3 through 6.5 contain some cases of apparently negative accommodation. These small errors probably arise from the use of a 'one-fits-all' calibration equation for the Autoref. Therefore the response levels in these figures should not be taken as absolute.

Relationship between Voluntary Ability and the Mandelbaum Effect

The Mandelbaum effect shows little variability in the sample, but memorised voluntary accommodation ability varies widely (Figure 6.6). For the mesh targets placed close to the dark focus, there is no significant correlation between the Mandelbaum effect and voluntary ability (Pearson $r = 0.4$, $p = 0.12$). However, with the mesh targets placed at 50 cm there is a significant correlation between the Mandelbaum effect and voluntary ability (Pearson $r = 0.62$, $p = 0.01$). A potential confounding factor in these correlations is that the dioptric distance between the C target and the mesh varied from subject to subject. I took the effects of the C target – mesh target separation into account using the method of partial correlations.[35]

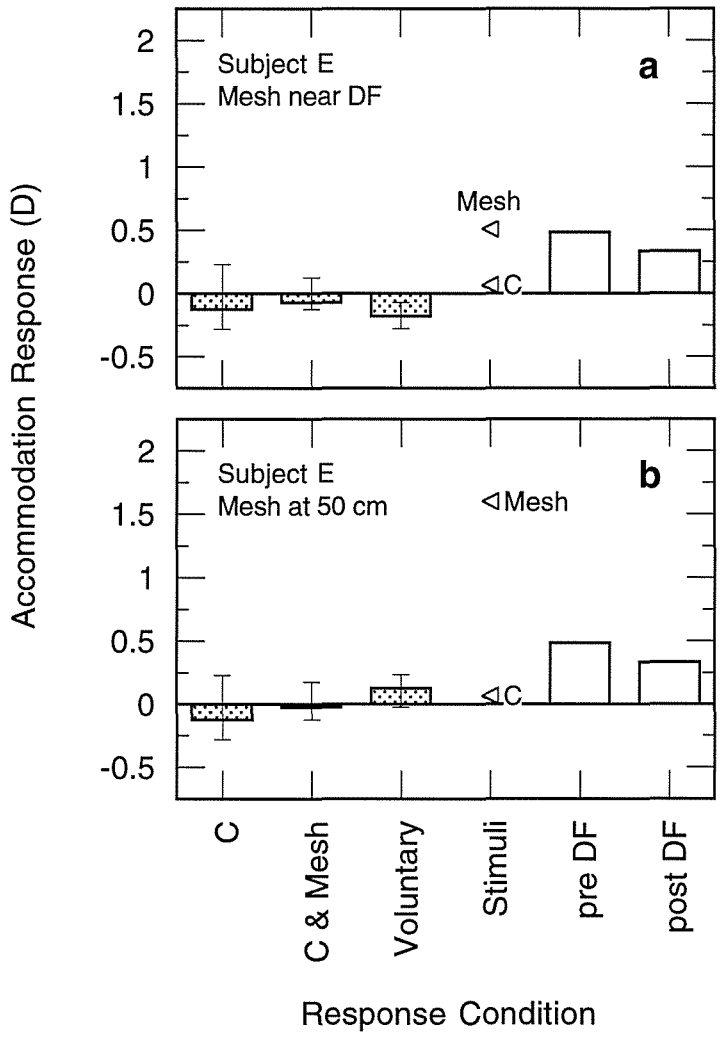


Figure 6.3. Accommodation responses of subject E. The median accommodation responses are plotted for the various conditions. The mesh targets were placed close to the individual dark focus level when required (**a**), or at a 50 cm distance when required (**b**). Error bars denote the total range of response values for this subject. Triangles denote the stimulus levels of the distant C target and the mesh targets. Pre- and post-task dark focus levels are also shown.

Partialling out the C target – mesh target separation had little effect on the correlations between the Mandelbaum effect and voluntary ability. The partial correlation between the Mandelbaum effect and voluntary ability with the C target – mesh target separation partialled out is not significant when the mesh is placed close to the individual dark focus

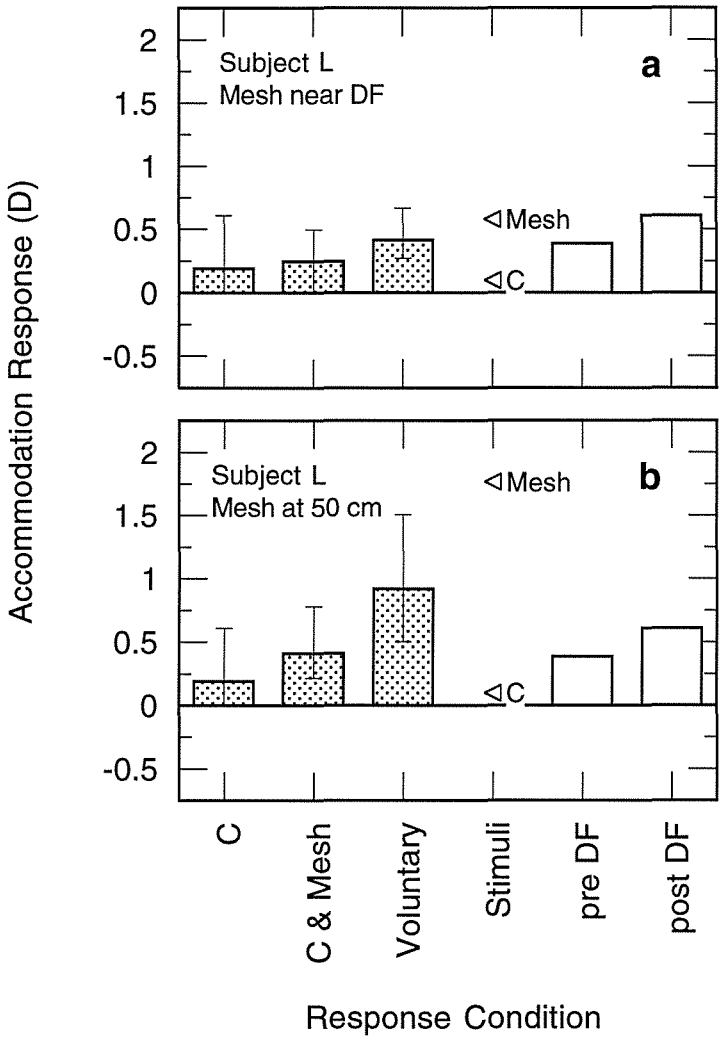


Figure 6.4. Accommodation responses of subject L. Conditions and explanations are as for Figure 6.3.

($r_{12.3} = 0.41, p = 0.12$), but is significant when the mesh is placed at 50 cm ($r_{12.3} = 0.71, p = 0.003$).

Although there is a significant correlation between the Mandelbaum effect and voluntary ability when the mesh is placed at 50 cm, this may be misleading if taken at face value. What is important is the nature of the association between the two variables. Principal axis regression was used to determine the slopes of the lines best describing the associations between the Mandelbaum effect and voluntary error for the two mesh distances.

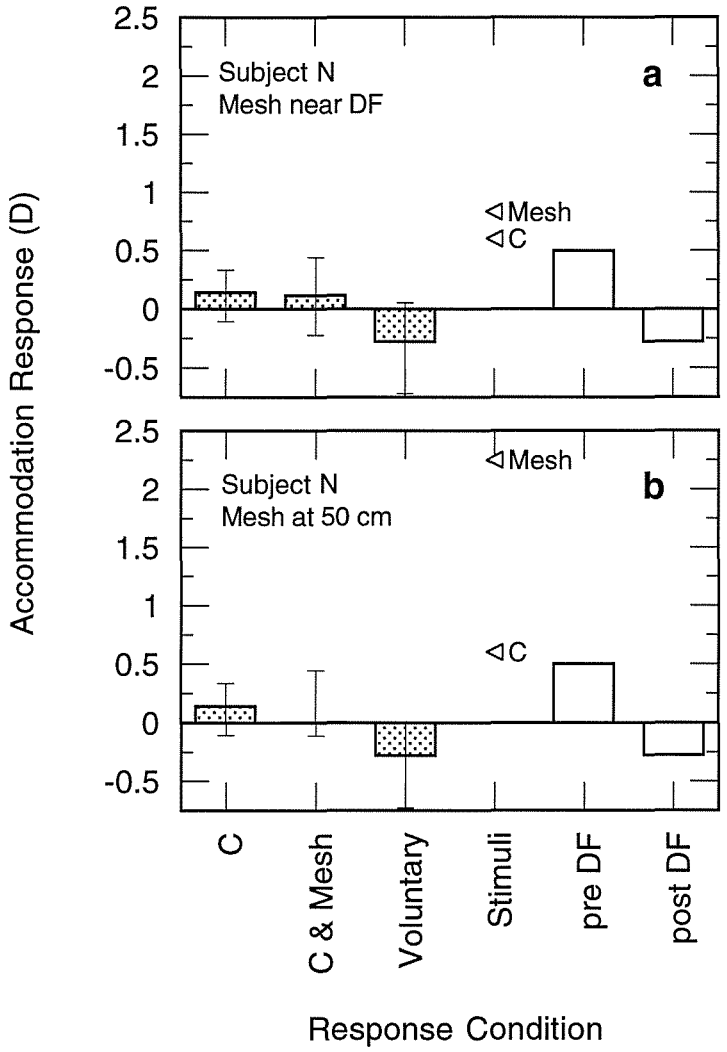


Figure 6.5. Accommodation responses of subject N. Conditions and explanations are as for Figure 6.3.

Principal axis regression lines are superimposed on the data in Figures 6.6a and 6.6b. Note that both lines have shallow slopes which are very different from the unit slope line. Approximate confidence intervals were calculated for the slopes of the two regression lines.[36] For the mesh placed close to the dark focus, a 95% confidence interval for the slope value encompasses the range -0.05 through +0.40. For the mesh placed at 50 cm, a 95% confidence interval for the slope value encompasses the range -0.03 through +0.16. Therefore it can be concluded with confidence that there is not a 1:1 relationship between the Mandelbaum effect and voluntary error. Moreover, the small values of the scatter plot slopes argue against a practical

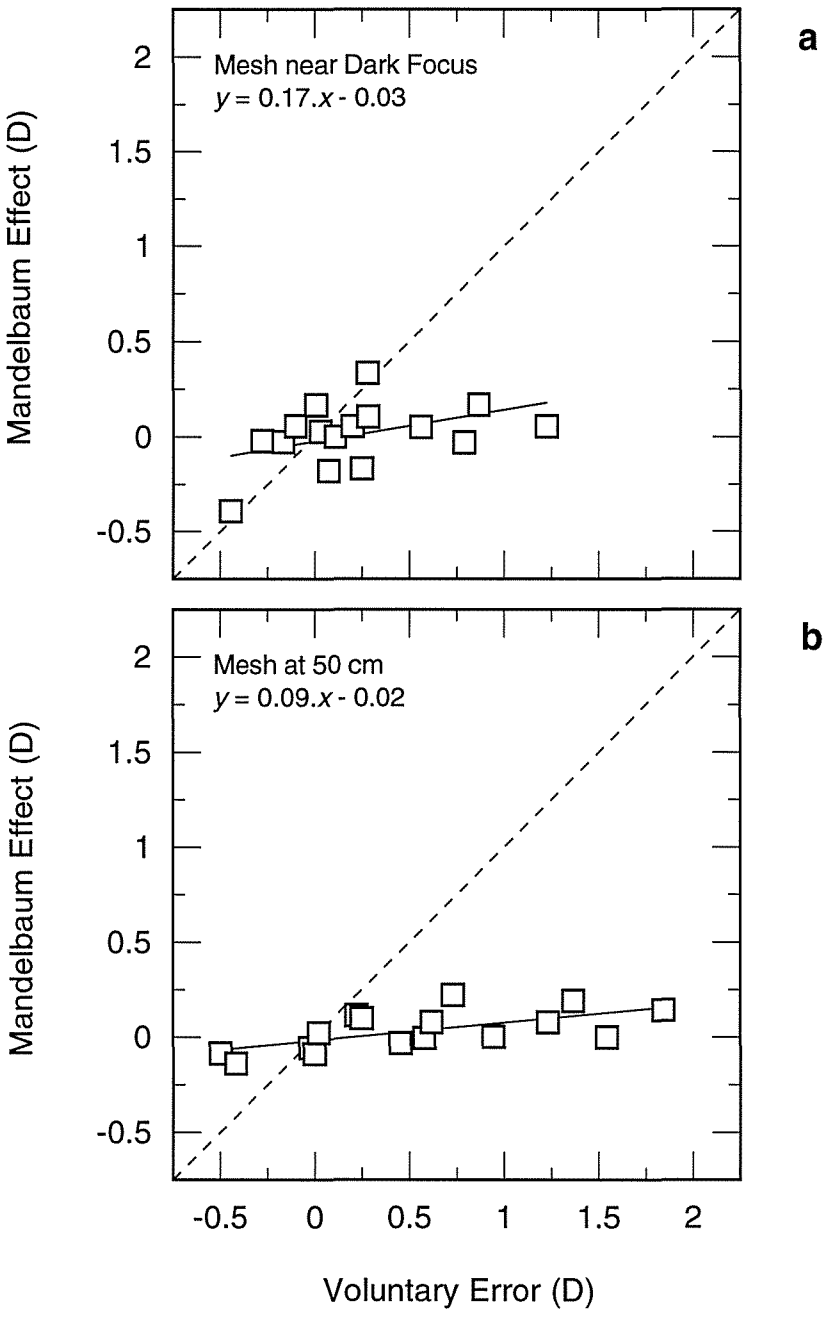


Figure 6.6. Mandelbaum effect as a function of voluntary error for mesh targets placed (**a**) close to the individual dark focus level or (**b**) at 50 cm (n = 16). Solid lines are principal axis regression lines. Dashed lines are unit slope lines. The Mandelbaum effect is the median response to the C target and mesh combination minus the median response to the C target alone. The voluntary error is the median response when attempting voluntary accommodation to the hidden C target minus the median response to the C target alone. See the text for details.

association between the Mandelbaum effect and voluntary ability. In the case of the mesh placed at 50 cm, the slope of 0.09 indicates that the Mandelbaum effect only improves by about 1/10 D for every 1 D change in voluntary accommodation ability.

The above conclusions apply to the group under study, but there is an alternative interpretation based on the results for individual subjects. The Mandelbaum effect and voluntary error values are quite different for some subjects (Figure 6.6), but close together for other subjects. The latter subjects could be using memorised voluntary accommodation to overcome the Mandelbaum effect, and the regression on group data would not make this distinction. To investigate this question I used the Mann Whitney U test to compare accommodation responses in the Mandelbaum Effect and Voluntary Ability conditions, individually for each subject. For the mesh placed near the individual dark focus, the accommodation responses were significantly different in the Mandelbaum Effect and Voluntary Ability conditions for 11/16 subjects at the 5% significance level, and for 8/16 subjects at the stringent Bonferroni level (0.3%). Similarly, for the mesh placed at 50 cm, the accommodation responses were significantly different in the Mandelbaum Effect and Voluntary Ability conditions for 14/16 subjects at the 5% level and for 13/16 subjects at the 0.3% level. Thus it is likely that most of the subjects were not using memorised voluntary accommodation during the Mandelbaum Effect task.

Magnitude of the Mandelbaum Effect and Voluntary Ability

The Mandelbaum effect does not vary much between subjects, but voluntary ability varies widely (Table 6.1). The mean Mandelbaum effect in the group is not significantly different from zero: in fact the maximum value of the Mandelbaum effect recorded is just 0.3 D. The mean voluntary error is only significantly different from zero when the mesh is placed at 50 cm. Individual dark focus values vary over a large range (Table 6.1), as expected.[38]

Table 6.1. Summary of the Mandelbaum effect, memorised voluntary accommodation, and dark focus values (n = 16)

Parameter	*Accommodation Response (D)*			*p**
	Mean	*Minimum*	*Maximum*	
Mandelbaum effect Mesh @ DF	0.0	-0.4	0.3	0.78
Mandelbaum effect Mesh @ 50 cm	0.0	-0.1	0.2	0.20
Voluntary error Mesh @ DF	0.2	-0.4	1.2	0.08
Voluntary error Mesh @ 50 cm	0.6	-0.5	1.8	0.006
Mean DF	0.6	0.0	1.7	-

*The results of paired t tests indicate the probabilities that the Mandelbaum effect and voluntary error are significantly different from zero. DF stands for dark focus.

Variability of Accommodation during the Conflicting Targets Tasks and during the Voluntary Task

Accommodation responses may be more variable in the Voluntary Accommodation condition than in the Mandelbaum effect condition when the mesh is at 50 cm (Table 6.2). The responses when viewing two conflicting targets are not significantly more variable than when viewing a single distant target. It should be noted though that while these conclusions apply to most subjects, there are some who do have more variable responses when there are conflicting targets or when exercising voluntary accommodation (Figure 6.7). For example, some subjects exhibited accommodation responses that varied by over 2.5 D when attempting voluntary accommodation with the opaque mesh at 50 cm (Figure 6.7).

Table 6.2. Comparisons of range of accommodation values in various conditions

Statistical Contrast	*Mesh Distance*	*Test Statistic:* $\hat{\psi}$
C *v.* C & Mesh	dark focus	-0.31
C *v.* C & Mesh	50 cm	0.25
C & Mesh *v.* Voluntary	dark focus	0.06
C & Mesh *v.* Voluntary	50 cm	-0.88*

The results are for post hoc comparisons following the Friedman test (see section C.2 for details). One contrast was significant at the 0.05 level and is denoted by an asterisk. A negative value of the test statistic ($\hat{\psi}$) indicates that the accommodation range was greater in the second condition of the pair. Critical values of the test statistic were: $\Delta = 0.87$ for $\alpha = 0.05$, and $\Delta = 1.05$ for Bonferroni $\alpha = 0.0125$.

Subject Perceptions

The subjects' responses to the question 'How did the target appear? Was it blurred or clear?' are summarised in Table 6.3. The subjects' responses to the question 'What were you trying to do while looking at the target?' are summarised in Table 6.4.

6.4. Discussion

Relationship between Voluntary Ability and the Mandelbaum Effect

The group data do not support the hypothesis that people use memorised voluntary accommodation to overcome the Mandelbaum effect (Figure 6.6). The slopes of the lines relating the Mandelbaum effect to memorised voluntary accommodation are low (Figure 6.6) and, importantly, the confidence intervals for the slopes do not include the value of +1. However an alternative interpretation of the results is that some subjects were using memorised voluntary accommodation while others were not using memorised voluntary accommodation. A regression analysis on group data

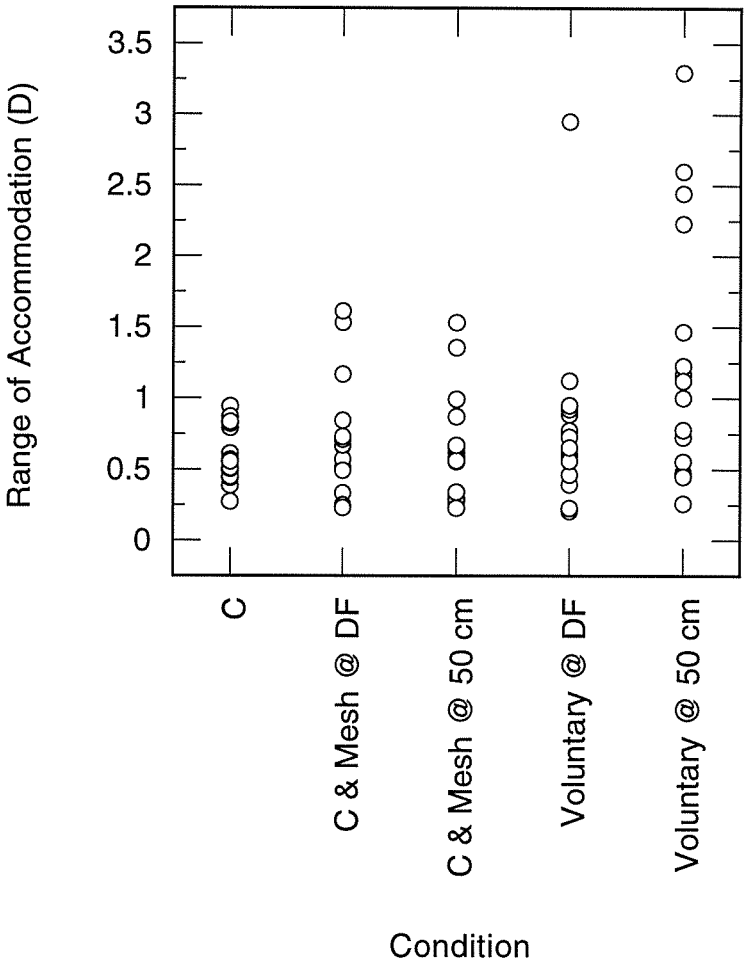


Figure 6.7. Accommodation response ranges for individual subjects and for the various trial conditions (n = 16). Note that this figure plots the accommodation response *range*, not the accommodation *response*.

would not distinguish between these two subject groups. However individual Mann Whitney U tests demonstrated that most subjects were unlikely to be using memorised voluntary accommodation in the Mandelbaum Effect task.

The findings of this study are probably dependent on the particular subject sample. For example, a greater range of Mandelbaum effect and memorised voluntary accommodation values may have been obtained in a sample of naive subjects. A sample of very experienced subjects may have shown a smaller spread of memorised voluntary accommodation values.

Table 6.3. Selected subject observations when the subject viewed the C target alone, the C target with mesh interposed, or when attempting voluntary accommodation

Subject Observation	*Proportion Subjects (/16)*		
	C target	*C & Mesh*	*Voluntary*
I. Changes in perceived size & distance			
1. Mesh on top of C & both at the same distance. This distance:			
a. unspecified		1	
b. further than both C & Mesh		1	
c. between C & Mesh		1	
d. closer than C & Mesh		1	
2. C closer than mesh		1	
3. C closer than mesh and vice versa alternately		1	
4. Mesh sometimes appears to move towards eye and become larger			1
II. Other observations			
5. Fading of target	2	2	1
6. Spurious resolution			1
7. Able to become completely unaware of mesh			1

Note that subjects could report more than one action per condition, so the columns do not necessarily total to sixteen.

In summary, it appears that many people do not use memorised voluntary accommodation to overcome the Mandelbaum effect. Their responses in the Mandelbaum effect and the voluntary accommodation tasks are too different for them to be using the same accommodation strategy in both situations. On the other hand, some people may use memorised voluntary accommodation to overcome the Mandelbaum effect.

Intuitively, memorised voluntary accommodation does not seem to be a good way of overcoming the Mandelbaum effect. Why rely on a memorised target position when there are visual cues (eg. blur and/or proximal cues)

Table 6.4. Self reported actions during the trials when the subject viewed the C target alone, the C target with mesh interposed, or when attempting voluntary accommodation

Category of Attempted Action, or Actual Action	*Proportion Subjects (/16)*		
	C target	*C & Mesh*	*Voluntary*
I. Indeterminate			
1. Nothing special	3	1	
II. Not related to targets			
2. Look in distance	1	1	1
3. Focus other room detail before start of trial, and then attempt to maintain same level of accommodation			1
4. Relax focus	1	2	3
5. Voluntary divergence		1	
III. Related to C target			
6. Look through or behind C		1	
7. Imagine a position of the C behind the mesh			4
8. Look at C, concentrate on C	5	9	
9. Focus on C	9	10	4
IV. Related to Mesh			
10. Ignore or don't concentrate on mesh		1	4
11. Look through or behind mesh		2	7
12. Look at centre of mesh			1
13. Keep mesh blurred		2	1
14. Focus further than mesh		2	2
V. Miscellaneous Actions			
15. Imagine a position of the C in front of mesh		1	
16. Not concentrating, daydreaming	1	2	1
17. Focus on C and mesh equally			1
18. Focus on C then mesh alternately		1	

Note that subjects could report more than one action per condition, so the columns do not necessarily total to sixteen.

available to obtain the desired focus directly? Furthermore, untrained subjects probably have poor memories for depth in three dimensional scenes. For example, Randle[6] found that untrained subjects could not maintain a distant focus while viewing a target in open-loop conditions (i.e. through a 0.5 mm pupil), although trained subjects could perform the task. Finally, in the real world objects of interest are usually not always the same distance from the eye. In this study the fixed distant target should have maximised the predicability of the target position, but in many real world situations it would be impossible to memorise target depth.

There are a number of possible voluntary accommodation strategies that people could use to focus away from a conflicting target. This study investigated memorised voluntary accommodation, but other voluntary strategies await study.

Magnitude of the Mandelbaum Effect and Voluntary Ability

MANDELBAUM EFFECT

A striking feature of the group data is the very narrow spread in values of the Mandelbaum effect contrasted with the wide spread in values of memorised voluntary accommodation (Figure 6.6 and Table 6.1). For the group as a whole, the Mandelbaum effect is not significantly different from zero (Table 6.1), although it does appear that some subjects depart from the group (Figure 6.6). The between-subject variability in values of the Mandelbaum effect was lower than observed in previous studies.[5,33,34] Some of these differences may be due to different subject instructions. In Owens' second experiment,[5] and the studies of Adams and Johnson,[33] and Rosenfield and Ciuffreda,[34] the instructions did not require the subjects to fixate a particular target. Some of the variability noted in these studies could be due to uncertainty as to which of the two conflicting targets should be fixated. The narrow spread in Mandelbaum effect values in this present study is unlikely to be due to subject experience as 5 of the subjects had no previous experience.

Collins *et al.* have made measurements of the Mandelbaum effect in natural conditions (i.e. reflections in VDT screens), and they only found a significant effect in some monocular viewing situations, and the effects were small (<0.25 D).[39] This present study and that of Collins *et al.* show that the Mandelbaum effect is either non–existent or small in natural viewing conditions.

It could be argued that the distant target provided a better stimulus to accommodation than the mesh target, and that this was the cause for the low Mandelbaum effect values. This seems unlikely given the design and spatial frequency content of the mesh, although this issue was investigated in a control experiment (see Chapter 7). Even when the contrast of the distant target was reduced to 0%, subjects generally still managed to overcome the Mandelbaum effect. Thus the target spatial detail and contrast characteristics are unlikely to have been a cause of the small Mandelbaum effect values. A possible explanation for the low Mandelbaum effect values in this study then is that the distant target provided better distance (spatiotopic) cues than the mesh targets. Some evidence supports this explanation while other evidence does not.

The distant target was placed on the rear wall of the laboratory, and the subject was familiar with the room dimensions. The walls of the room and other furniture in the room provided perspective cues to depth. On the other hand the mesh in the Mandelbaum task was simply suspended by a clip from a stand. Furthermore, the meshes used in this experiment had constant angular dimensions, but objects in the real world appear to get larger as they get closer to the eye. The subjects may have been using proximal cues provided by the distant target to overcome the strong blur cues and weak proximal cues provided by the meshes. When the subject viewed the opaque mesh target, the proximal cues provided by the distant target were unavailable, and so the blur and proximal cues of the opaque mesh dominated the response.

There are some anomalies in the argument that subjects were using proximal cues to overcome the Mandelbaum effect. When the subjects

viewed the opaque mesh, the perspective cues in the peripheral field of view should still have provided information on the depth of the hidden distant target. However, many subjects were not able to relax their focus very well from the opaque mesh, and so may not have been using these cues. Perhaps though, the opaque mesh provided stronger central blur cues than the peripheral proximal cues provided by the laboratory.

VOLUNTARY ABILITY

The large spread in memorised voluntary accommodation values (Figure 6.6 and Table 6.1) were partially expected given the between-subject difference noted in other voluntary tasks.[2-4] Three previous studies have attempted to train memorised voluntary accommodation.[6,10,12] Randle found that some subjects required extensive practice before they could hold a stable memorised voluntary accommodation response, even when auditory feedback was provided.[6] Holding a high accommodation response level in the presence of a distant conflicting target was more difficult than holding a low response level in the presence of a near conflicting target.

Variability of Accommodation during the Conflicting Targets Tasks and during the Voluntary Task

The memorised voluntary accommodation response was not more variable than the Mandelbaum effect response in the group as a whole when the mesh was close to the dark focus, but it was more variable when the mesh was at 50 cm (Figure 6.7 and Table 6.2). (This is further evidence that many of the subjects were not using the same accommodation strategy in the Mandelbaum effect and voluntary conditions.) The variability of the voluntary response has not previously been studied. There are two potential sources for increased variability in memorised voluntary accommodation. Firstly, the response may be more variable simply due to subject uncertainty and an inability to hold a steady response. Secondly, accommodation generally becomes more variable as the mean response level increases.[40] Studies attempting to train voluntary accommodation have generally

concentrated on the ability to obtain a specific mean level of accommodation. However a highly variable voluntary accommodation response may intermittently degrade acuity and cause a person to miss a briefly presented object.

The response to the Mandelbaum effect task is not more variable than the response to the distant C target (Figure 6.7 and Table 6.2). Thus the mesh was unable to induce a Mandelbaum effect in most subjects, and it was also unable to make the response more variable. Adams and Johnson[33] stated that the fluctuations of accommodation in a Mandelbaum task did not depend on target dioptric separation, and were also similar to those reported in other studies for responses to single targets. However, they did not report standard deviations or the results of power spectrum analysis. Rosenfield and Ciuffreda[34] also considered the response variability under the Mandelbaum effect and found that the standard deviations did not vary greatly with the dioptric separation of the two conflicting targets. Nevertheless, some subjects do have more variable responses in a Mandelbaum task (Figure 6.7).

In considering the variability of the responses, the method of data collection must be taken into account. I took readings with the Autoref approximately every 5–10 seconds during a trial. As a measure of variability I used the range of accommodation. It may be that the Mandelbaum effect leads to changes in the high frequency fluctuations of accommodation, but this has not been specifically investigated to date.

Subjects' Perceptions of their Actions

There is a wide variety in the subjects' reports of their attempted or actual actions during the experiment (Table 6.4). In the Mandelbaum effect task, subject L (Table 6.4, category 5) noted on one trial that when the mesh became clear, she felt as if she had to diverge her eyes to bring the distant target clear. This subject in the previous semester had been prescribed pencil push-up exercises by her optometrist, and these had probably made her aware of her voluntary near response. A few subjects said they were trying

to keep the mesh blurred (Table 6.4, category 13). Thus they were probably using the amount of perceived blur of the mesh as a spatiotopic cue: when the mesh became more blurred, they knew they were (probably) focusing in the correct direction towards the C target.

Subject N noted in the trials of the Mandelbaum effect that the mesh did not appear to be in front of the C target. Rather, the mesh looked like 'background colour', and both the mesh and the C target appeared to be at the same distance. The subject attempted to 'bring the C out front and put the cross hairs behind' (Table 6.4, category 15).

Finally, subject G did not use any consistent strategy throughout the session. In some of the trials of the Mandelbaum effect, she focused on the C and mesh intermittently (Table 6.4, category 18), changing to the opposite target when she was tired. Then in one trial she daydreamed (Table 6.4, category 16), and in another did not concentrate on either target, but just looked at them (Table 6.4, category 16). In the trials of her voluntary accommodation she looked at the centre of the mesh (Table 6.4, category 12), or looked behind the mesh (Table 6.4, category 11), and then halfway through one trial was 'trying to focus' (Table 6.4, category 9). This subject was retained in the study, despite her erratic responses, because this may be her normal approach in the real world.

Interesting Subject Perceptions

All the subjects reported on target clarity or blur during the course of the session. In addition, some subjects volunteered other information on what they were observing during the session. A few subjects noted a fading of the target on some trials (Table 6.3, category 5). Whether this was due to the Troxler phenomenon, or to binocular rivalry (the left eye saw a dark field) is uncertain. However, when observed, subjects were advised not to stare in exactly the same point but to look at different points on the distant target. One subject noted the lines of the mesh alternate from black on white to white on black with changes in focus, and I attributed these observations to spurious resolution (Table 6.3, category 6). Finally one subject noted in the

voluntary task that he was able to completely remove the mesh from his awareness (Table 6.3, category 7), similar to Mandelbaum in his original paper.[1]

Changes in Perceived Size and Distance

The most interesting reports by the subjects were changes in the perceived sizes and distances of the targets. These effects are collected in Table 6.3 (categories 1–4). In the Mandelbaum effect trials, four subjects perceived the mesh to be placed on top of the C target, but close to the C target (Table 6.3, category 1). Subject G did not say what this apparent distance was. Subject N thought the targets appeared to be at a single distance more distant than the actual C target and mesh. Subject I thought the targets appeared to be at a single distance between the actual positions of the C target and mesh. Subject E thought the targets appeared to be at a single distance nearer than the actual distances of the C target and mesh. In addition, Subject I sometimes perceived the C target to be closer than the mesh in one trial (Table 6.3, category 2), and alternating in apparent distance on one trial (Table 6.3, category 3). The subjects *were aware that these were illusions*, because (except for subject G) they were able to compare the perceived distances to the known distances of the targets. There are some possible explanations for these effects.

When a real distant scene is viewed through a window frame, there is a perceptual flattening of the scene.[41] In the absence of cues to depth, objects at different distances tend to be localised at a single intermediate distance.[42] Possibly, the mesh in this study provided a flatness cue which made the distant target and mesh appear as if they were closer together. However this does not explain why subjects differed in their perception of the distance at which the target pair appeared to lie. A possibility is the use of accommodation response level as a cue to perceived distance.[43] As perceived distance is inversely related to accommodation response level,[43] a subject with a higher than normal accommodation response (for whatever reason)

would perceive the targets as closer, and a subject with a lower accommodation response would perceive the targets as farther away.

Some of the observed changes in perceived target distance may relate to Gestalt figure-ground relationships.[44] Sometimes when a subject focused accurately for the distant target, the mesh became very blurred appearing as a 'background colour' (Subject N) or as a motley bubbly material in the background (Subject G). To these subjects the mesh may have appeared as a *ground* on which the *figure*, the C target, rested.

Finally, accommodation micropsia or macropsia may have affected the subjects' perception of target size, and then indirectly, their distance perception.[45] Subject L noted that when she attempted to look through the mesh in the Mandelbaum effect task, it appeared to move towards her and appeared to become larger. The increase in apparent size could have been due to relaxed accommodation and accommodation macropsia.

The Role of Distance Cues in the Mandelbaum Effect

A number of lines of evidence suggest that proximal cues to accommodation may play a role in the Mandelbaum effect. In his study, Mandelbaum noted that head movements could be used to overcome the unwanted accommodation response to a window screen.[1] Head movements may have aided Mandelbaum by blurring the contrast gradient of the screen detail relative to the stable distant target.[46] However there is an alternative interpretation of Mandelbaum's observations. Maybe the screen disrupts distance perception, leading to a perceptual flattening of the scene.[41,42] The parallax cue provided by head movements would allow precise determination of the distance of the window screen.[47,48] With these distance cues it may then be possible to focus more correctly for the desired object.

The absence of significant Mandelbaum effect values in this study may be due to the proximal stimuli to accommodation provided by the laboratory conditions. Collins *et al.* also did not find a notable Mandelbaum effect in natural viewing conditions.[39]

Some of the subjects in this study reported changes in the perceived sizes and distances of the targets. Possibly the mesh target leads to a perceptual flattening of the scene. Gestalt figure–ground relationships may lead to incorrect perceptions of target depth. Finally, changes in perceived size and distance may be due to accommodation micropsia. These subject perceptions raise an interesting question: Is the Mandelbaum effect a response to conflicting and inappropriate proximal cues, or is the Mandelbaum effect due to conflicting blur cues?

There may even be an interaction between proximal and blur cues in the Mandelbaum effect. For example, suppose that a mesh was placed between a subject and a distant scene. Suppose then that the subject makes an unwanted response to the blur cues provided by the mesh. This increase in accommodation would cause a reduction in the perceived sizes of the targets through accommodation micropsia. The change in perceived size may then act as a looming (changing size) cue[49,50] which would again stimulate accommodation directly through proximal accommodation. The change in accommodation would induce a change in perceived size and so on, and so on. These interactions are speculative but not unreasonable.

6.5. Summary

1. Many people do not use memorised voluntary accommodation to overcome the Mandelbaum effect, that is, they do not overcome the Mandelbaum effect by locking on to a focus level for the memorised distance of the desired target. Some people may use memorised voluntary accommodation to overcome the Mandelbaum effect but there is no way of determining this from the experimental design used in this study.
2. There was not a significant Mandelbaum effect in the group, and the highest recorded value of the Mandelbaum effect was just 0.3 D. The definite instruction in this study requiring attention to only one of the conflicting targets may have reduced the Mandelbaum effect. It

is also possible that subjects used the proximal cues provided by the more distant target to overcome the unwanted accommodation response to the blur cues of an intervening mesh target.

3. In contrast to the Mandelbaum effect, memorised voluntary accommodation ability varies widely in the group of subjects who participated in this study.
4. For most subjects, accommodation is not more variable when viewing conflicting targets than when viewing a single target. However some subjects appear to have more variable responses when viewing conflicting targets.
5. The accommodation response may be more variable when attempting memorised voluntary accommodation than when viewing conflicting targets. This further suggests that people are not using the same accommodation strategies in both situations.
6. Some subjects observe changes in the perceived sizes and distances of conflicting targets presented in real space. These observations may be due to perceptual flattening of the three dimensional scene by the intervening mesh, Gestalt figure–ground relationships, or accommodation micropsia.
7. Proximal accommodation may play a role in the Mandelbaum effect. This speculation is based on two observations. Firstly, some subjects noted changes in the perceived sizes and distances of targets in the Mandelbaum effect task. Also, the Mandelbaum effect remains small even when the contrast of a desired target is degraded compared to the conflicting target (see Chapter 7). This suggests that subjects use proximal cues to overcome the unwanted response to the blur cues of an intervening mesh.

References

1. Mandelbaum, J. An accommodation phenomenon. *A. M. A. Arch. Ophthalmol.* 1960, **63**, 923–926.
2. Marg, E. An investigation of voluntary as distinguished from reflex accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1951, **28**, 347–356.

3. McLin, L.M. and C.M. Schor. Voluntary effort as a stimulus to accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1988, **29**(11), 1739–1746.
4. Jaschinski-Kruza, W. On proximal effects in objective and subjective testing of dark accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**, 328–334.
5. Owens, D.A. The Mandelbaum effect: Evidence for an accommodative bias toward intermediate viewing distances. *J. Opt. Soc. Am.* 1979, **69**(5), 646–652.
6. Randle, R.J. Volitional control of visual accommodation. *In: Conference Proceeding No. 82 on Adaptation and Acclimatization in Aerospace Medicine.* AGARD, NATO, 1971.
7. Cornsweet, T.N. and H.D. Crane. Training the visual accommodation system. *Vision Res.* 1973, **13**, 713–715.
8. Provine, R.R. and J.M. Enoch. On voluntary ocular accommodation. *Percept. Psychophys.* 1975, **17**(2), 209–212.
9. Trachtman, J.N. Biofeedback of accommodation to reduce myopia: a review. *Am. J. Optom. Physiol. Opt.* 1987, **64**(8), 639–643.
10. Randle, R.J. Responses of myopes to volitional control training of accommodation. *Ophthalmic Physiol. Opt.* 1988, **8**(3), 333–340.
11. Gilmartin, B., L.S. Gray and B. Winn. The amelioration of myopia using biofeedback of accommodation: a review. *Ophthalmic Physiol. Opt.* 1991, **11**, 304–313.
12. Roscoe, S.N. and D.H. Couchman. Improving visual performance through volitional focus control. *Hum. Factors.* 1987, **29**(3), 311–325.
13. Phillips, S.R. *Ocular Neurological Control Systems: Accommodation and the Near Response Triad.* PhD Thesis. Berkeley: University of California, 1974. pp. 343–359
14. Charman, W.N. and J. Tucker. Dependence of accommodation response on the spatial frequency spectrum of the observed object. *Vision Res.* 1977, **17**, 129–139.
15. Phillips, S. and L.W. Stark. Blur: a sufficient accommodative stimulus. *Doc. Ophthalmol.* 1977, **43**(1), 65–89.
16. Charman, W.N. and J. Tucker. Accommodation and color. *J. Opt. Soc. Am.* 1978, **68**(4), 459–471.
17. Ciuffreda, K.J. and S.C. Hokoda. Effect of instruction and higher level control on the accommodative response spatial frequency profile. *Ophthalmic Physiol. Opt.* 1985, **5**(2), 221–223.
18. Campbell, F.W. and G. Westheimer. Dynamics of accommodation responses of the human eye. *J. Physiol.* 1960, **151**, 285–295.
19. Ciuffreda, K.J. and P.B. Kruger. Dynamics of human voluntary accommodation. *Am. J. Optom. Physiol. Opt.* 1988, **65**(5), 365–370.
20. Malmstrom, F.V. and R.J. Randle. Visual imagery in the third dimension: voluntary control of accommodation. *In: Proceedings of Psychology in the Air Force Symposium.* USAF Academy, Colorado: Department of Life and Behavioral Sciences, 1974. pp. 189–192.
21. McBrien, N.A. and M. Millodot. Clinical evaluation of the Canon Autoref R-1. *Am. J. Optom. Physiol. Opt.* 1985, **62**(11), 786–792.
22. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 38–39.
23. Peli, E. Contrast in complex images. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1990, **7**(10), 2032–2040.
24. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.

25. Ciuffreda, K.J., M. Dul and S.K. Fisher. Higher-order spatial frequency contribution to accommodative accuracy in normal and amblyopic observers. *Clin. Vision Sci.* 1987, **1**(3), 219–229.
26. Tucker, J. and W.N. Charman. Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 137–142.
27. Owens, D.A. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980, **20**, 159–167.
28. Ciuffreda, K.J. and D. Rumpf. Contrast and accommodation in amblyopia. *Vision Res.* 1985, **25**(10), 1445–1457.
29. Schor, C.M., J.C. Kotulak and T. Tsuetaki. Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. *Invest. Ophthalmol. Visual Sci.* 1986, **27**(5), 820–827.
30. Rosenfield, M. and K.J. Ciuffreda. Effect of surround propinquity on the open-loop accommodative response. *Invest. Ophthalmol. Visual Sci.* 1991, **32**, 1, 142–147.
31. Rosenfield, M., K.J. Ciuffreda and G.K. Hung. The linearity of proximally induced accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1991, **32**(11), 2985–2991.
32. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin.* 1972, **77**(1), 54–64.
33. Adams, C.W. and C.A. Johnson. Steady-state and dynamic response properties of the Mandelbaum effect. *Vision Res.* 1991, **31**(4), 751–760.
34. Rosenfield, M. and K.J. Ciuffreda. Accommodative responses to conflicting stimuli. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1991, **8**(2), 422–427.
35. Pedhazur, E.J. *Multiple Regression in Behavioral Research. Explanation and Prediction.* 2nd ed. New York: Holt, Rinehart and Winston, 1982. pp. 97–134.
36. Sokal, R.R. and F.J. Rohlf. *Biometry.* 2nd ed. San Francisco: W. H. Freeman, 1981. pp. 594–601.
37. Marascuilo, L.A. and M. McSweeney. *Nonparametric and Distribution-Free Methods for the Social Sciences.* Monterey, CA: Brooks/Cole, 1977.
38. Leibowitz, H.W. and D.A. Owens. New evidence for the intermediate position of relaxed accommodation. *Doc. Ophthalmol.* 1978, **46**(1), 133–147.
39. Collins, M., B. Davis and D. Atchison. VDT screen reflections and accommodation response. *Ophthalmic Physiol. Opt.* 1994, **14**, 193–198.
40. Miege, C. and P. Denieul. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 165–171.
41. Eby, D.W. and M.L. Braunstein. The perceptual flattening of 3D scenes enclosed by a frame [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1184.
42. Gogel, W.C. Equidistance tendency and its consequences. *Psychological Bulletin.* 1965, **64**(3), 153–163.
43. Fisher, S.K. and K.J. Ciuffreda. Accommodation and apparent distance. *Perception.* 1988, **17**, 609–621.
44. Bruce, V. and P.R. Green. *Visual Perception: Physiology, Psychology and Ecology.* 2nd ed. Hove, East Sussex, U.K: Lawrence Erlbaum Associates, 1990. pp. 05–139.
45. Benel, R.A. *Visual Accommodation, the Mandelbaum Effect, and Apparent Size.* PhD thesis. Urbana-Champaign: University of Illinois, 1979.

46. Hung, G.K. and K.J. Ciuffreda. Accommodative responses to eccentric and laterally-oscillating targets. *Ophthalmic Physiol. Opt.* 1992, **12**, 361–364.
47. Ogle, K.N. *Researches in Binocular Vision.* 2nd printing. New York: Hafner, 1964. p. 134.
48. Rogers, B. and M. Graham. Motion parallax as an independent cue for depth perception. *Perception.* 1979, **8**, 125–134.
49. Kruger, P.B. and J. Pola. Changing target size is a stimulus for accommodation. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1985, **2**(11), 1832–1835.
50. McLin, L.N., C.M. Schor and P.B. Kruger. Changing size (looming) as a stimulus to accommodation and vergence. *Vision Res.* 1988, **28**(8), 883–898.

Chapter 7

Target Contrast and the Mandelbaum Effect

7.1. Introduction

The aim of this study is to determine if the findings of Chapter 6 on the relationship between the Mandelbaum effect and voluntary accommodation can be partly attributed to the adequacy of the distant target as a stimulus to accommodation. In that study, subjects viewed a distant letter target in the control condition, the same letter through an interposed mesh in the Mandelbaum effect condition, or an opaque mesh in the memorised voluntary accommodation condition. In the memorised voluntary accommodation condition the subject's task was to focus for the remembered distance of the obscured distant target. This present study repeats those conditions, but varies the adequacy of the distant target as a stimulus to accommodation by changing its contrast.

The study described in Chapter 6 found that many subjects do not use memorised voluntary accommodation to overcome the Mandelbaum effect, that is, they do not overcome the Mandelbaum effect by locking on to the remembered focus position of a distant target. An important feature of the group data was the very narrow spread in the values of the Mandelbaum effect compared with the wide spread of values in the memorised voluntary accommodation task. The large difference between the values of the Mandelbaum effect and the values of memorised voluntary accommodation suggested that subjects could not have been using the same accommodation strategy in both conditions.

One possible interpretation of these results is that the interposed mesh target did not provide a sufficiently powerful stimulus to accommodation. According to this interpretation, subjects focused for the distant letter target, and had no difficulty overcoming an unwanted response to the conflicting mesh target. Perhaps if the mesh had provided a more powerful stimulus to accommodation then subjects might have shown greater Mandelbaum effects, and thus the accommodation responses in the Mandelbaum effect condition and the voluntary accommodation condition would have been more similar.

The Mandelbaum effect values in the previous study (n = 16) only varied between -0.4 D and 0.3 D when the intervening mesh was placed close to the individual dark focus, and between -0.1 D and 0.2 D with the intervening mesh placed at 50 cm. Furthermore the mean Mandelbaum effect was not significantly different from zero when the mesh was placed either close to the individual dark focus (p = 0.78) or at 50 cm (p = 0.2). However, based on previous research, the mesh should have provided a good stimulus to accommodation.

The mesh target is composed of medium to high contrast (40–60%) black vertical and horizontal crossing limbs. The contrast of the mesh target should be adequate to provide a good stimulus to accommodation (see section 1.5.1.2).[1] The limbs of the mesh are 3 minute arc wide separated by 6 minute arc gaps, and the fundamental grating frequency of

6.7 cycles.degree^{-1} should provide a good stimulus to accommodation (see section 1.5.1.1).[2] Furthermore, the mesh spacing is such that regardless of the subject's direction of gaze, grating detail is always present no greater than 3 minute arc from the fixation point. Target detail at 3 minute arc eccentricity should provide an adequate stimulus to accommodation (see section 1.5.4).[3] The distant target is a block of medium to high contrast (55–68%) black on white 6/60 Landolt C's. The distant target contains more low spatial frequency information than the mesh target, but otherwise would not be expected to provide a better stimulus to accommodation than the mesh target.

To determine if target characteristics did play a part in the findings of the previous study, I decided to repeat the study using distant letter targets of different contrasts. I predict that the Mandelbaum effect to an intervening mesh will be greatest for low contrast distant targets. Benel has previously shown that target contrast can influence the Mandelbaum effect.[4] Benel varied the contrast of the intervening mesh, whereas in this present study I keep the contrast of the intervening mesh constant while varying the contrast of the distant fixated target.

7.2. Methods

Subjects

Five subjects participated in the study. One subject was excluded due to computer data loss. The four subjects remaining were aged between 17 and 39 years of age, and had right eye subjective amplitudes of accommodation (4.2–9.5 D using a Rodenstock Hand Optometer) sufficient for the tasks involved in the experiment. Right eye visual acuities ranged between 6/3.8 and 6/6. Best sphere refractive errors in the right eye ranged between -1.87 DS and +0.5 DS, and cylindrical component of the refractive error were less than or equal to 0.50 DC. Three of the subjects had participated in the previous study (see Chapter 6), and were available to participate in this study. Two of these were chosen because they demonstrated relatively poor

memorised voluntary accommodation, and one subject was chosen because he had demonstrated relatively good memorised voluntary accommodation. Between 35 and 84 days had passed since these subjects had participated in the study of Chapter 6. The fourth subject was a member of the public with no previous experience in accommodation studies.

Apparatus

OPTOMETER

Accommodation was measured with a Canon Autoref R-1 infra-red optometer (see Appendix A). The use of the Autoref in this study was identical to that described in Chapter 6 (see section 6.2 - 'Apparatus').

TARGETS

The targets used in this study (Figure 7.1) were very similar to those used in the study of Chapter 6. The transparent and opaque mesh targets used in this study were identical to those used in the previous study (Figure 7.1b,c), except that the opaque mesh had a white surround rather than a black surround. The luminance of the white portions of the opaque mesh target ranged between 22 $cd.m^{-2}$ and 45 $cd.m^{-2}$. The distant target was similar to that of the previous study, except that 4 different target contrasts were used and the black surround field was changed to a white surround field (Figure 7.1a). The white surround field was used (rather than a black surround field) to push the outer border further into the periphery so that it would provide a weaker peripheral stimulus to accommodation (compare Figures 6.2a & 7.1a). The target consisted of a block of 6/60 Snellen equivalent Landolt C's which were grouped on a white square having a side of 9.6°. The Landolt C's were separated from each other by 25 minute arc. The distant target was viewed at a distance of 3.8 m. The contrast of the Landolt C's was varied using a halftone process, and the halftone dots were not visible to the subjects. Four distant targets were produced in which the Landolt C's had estimated Michelson contrasts[5] of 68%, 16%, 5% and 0%. Due to the reproduction process, the 16% and 5% contrast targets were not absolutely

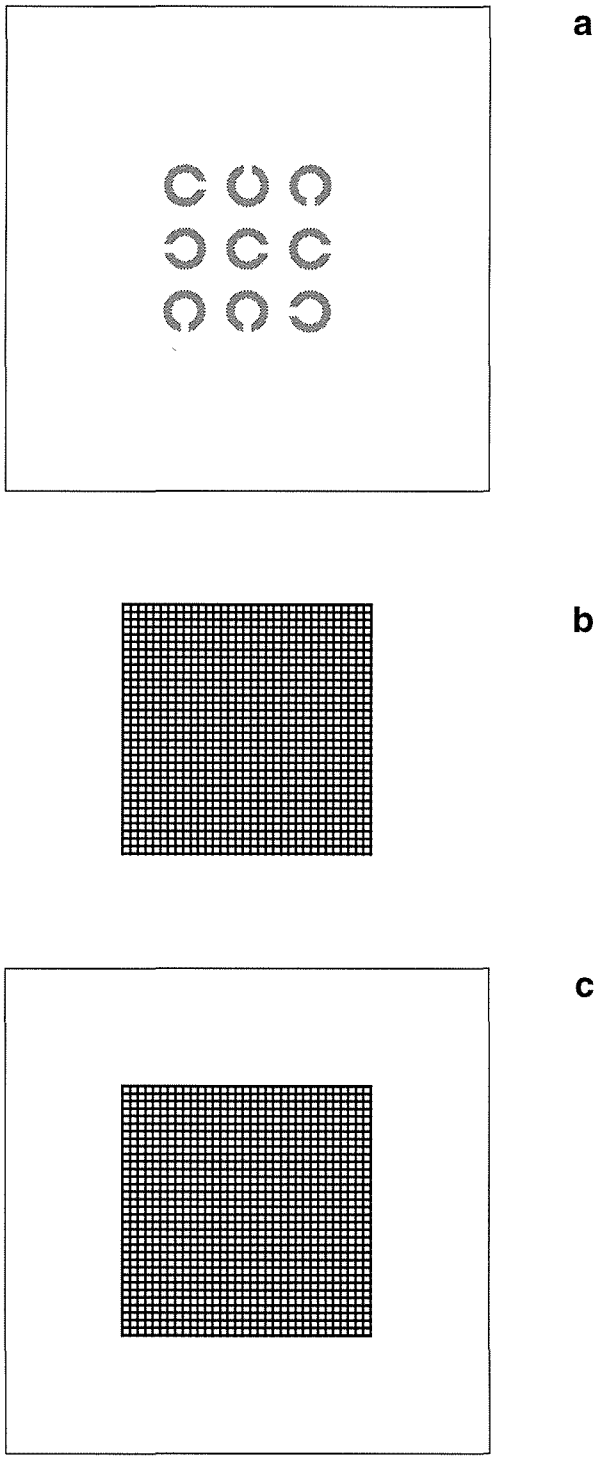


Figure 7.1. (**a**) The distant Landolt C target, (**b**) the mesh on a transparent background, and (**c**) the mesh on an opaque background. The distant Landolt C target is shown here with a simulated low contrast level. The halftone dots in the actual target were not visible to the subject. Distant target contrasts of 68%, 16%, 5% and 0% were used. The angular dimensions are drawn to scale.

uniform in contrast. The luminance of the white portion of the distant target ranged between 37.5 $cd.m^{-2}$ and 50 $cd.m^{-2}$.

Procedure

The procedure was similar to that of the previous study. I first performed a 'maximum plus' subjective refraction for the subject's right eye and recorded visual acuity. Cylindrical components of 0.25 DC and 0.50 DC were left uncorrected in subjects I and B respectively. Throughout the experiment right eye monocular viewing was used, and the subject's left eye was patched.

I then made pre-task measurements of the subject's dark focus. The subject first sat in the completely darkened experimental room for 5 minutes to allow any possible tonic adaptation effects to subside. Several readings of dark focus were then made while the subject was instructed to 'look straight ahead at the end of the room.'

I then measured the accommodation response in eight different stimulus conditions presented in counterbalanced order for a total of two trials of each condition.[6] The eight conditions were:

1. A block of 68% contrast 6/60 Landolt C's at a distance of 3.8 m;
2. A block of 16% contrast 6/60 Landolt C's at a distance of 3.8 m;
3. A block of 5% contrast 6/60 Landolt C's at a distance of 3.8 m;
4. A block of 0% contrast 6/60 Landolt C's at a distance of 3.8 m;
5. The 68% contrast Landolt C's of (1) with a Mesh superimposed close to the estimated individual dark focus value;
6. The 16% contrast Landolt C's of (2) with a Mesh superimposed close to the estimated individual dark focus value;
7. The 5% contrast Landolt C's of (3) with a Mesh superimposed close to the estimated individual dark focus value;
8. The 0% contrast Landolt C's of (4) with a Mesh superimposed close to the estimated individual dark focus value.

Note that one trial of each condition was first performed, then followed by a second trial of each condition, to give a total of 16 trials. When in place

the mesh was placed close to the individual dark focus position. Only one mesh distance was used to reduce session time. During the above trials the subject was instructed:

> You must keep your head very still while measurements are being taken. You should look at the middle C on the wall and view it naturally, the same as you would when normally reading a book or sign at the same distance.

The advantages of this instruction are discussed in the previous study (see section 6.2 - 'Procedures'). Additionally, if the subject could not see the distant target because its contrast was too low, the subject was instructed:

> Some of the letters have a very low contrast, and will be difficult to see. If you cannot see the letter, look in the direction of the centre letter and view the target as you would when normally looking at the letter.

This instruction was necessary to prevent the subject from losing attention, and adopting variable positions of gaze and focus.

Immediately after these 16 trials, estimates were made of the subject's memorised voluntary accommodation ability. The subject viewed a mesh similar to that used in conditions (5) through (8) above but on an opaque (rather than transparent) background (Figure 7.1c). In this condition (9) the opaque mesh was placed at the individual dark focus, and two trials were performed. Before taking measurements I encouraged the subject to obtain a good view of the room to maximise proximal awareness. Subjects were instructed:

> Look at the centre of the mesh pattern, but ignore the mesh pattern. Imagine you are looking at the letter C on the wall behind the mesh pattern. Focus your eyes to the distance of the letter C, the same as you would when normally focusing on the letter C.

I made ten readings of accommodation at each trial with the Autoref. I measured horizontal pupil diameter at the start of each trial, and mean pupil

size varied in the range 4.3–6.1 mm. At the end of each trial I asked the subjects the following questions:

1. How did the target appear? Was it blurred or clear?
2. What were you trying to do while looking at the target?

Dark focus was measured post-task in the same way that it had been measured pre-task.

Analysis

The ocular refraction, and stimuli to and responses of accommodation were calculated in the same way as they had been in Chapter 6 (see section 6.2 - 'Analysis' & Appendix E).

CALCULATION OF REGRESSION ANALYSIS PARAMETERS

As a measure of the *Mandelbaum effect,* I subtracted the median response when viewing the C target alone from the median response when viewing the C target with mesh interposed, that is,

$$ME_{68} = AR_{C68M} - AR_{C68} \,, \tag{7.1}$$

$$ME_{16} = AR_{C16M} - AR_{C16} \,, \tag{7.2}$$

$$ME_{5} = AR_{C5M} - AR_{C5} \,, \tag{7.3}$$

$$ME_{0} = AR_{C0M} - AR_{C0} \,, \tag{7.4}$$

where:

ME_{68}, ME_{16}, ME_{5} and ME_{0} are measures of the Mandelbaum effect when the mesh was placed at the individual dark focus level, for C target contrasts of 68%, 16%, 5% and 0% respectively;

AR_{C68M}, AR_{C16M}, AR_{C5M} and AR_{C0M} are the median accommodation responses in the respective second trials when the C targets were viewed with a mesh interposed at the individual dark focus level, for C target contrasts of 68%, 16%, 5% and 0% respectively;

AR_{C68}, AR_{C16}, AR_{C5} and AR_{C0} are the median accommodation responses in the respective second trials when the C target was viewed alone, for C target contrasts of 68%, 16%, 5% and 0% respectively.

As a measure of voluntary accommodation (the *voluntary error*), I subtracted the median response when viewing the C target alone from the median response when attempting to voluntarily focus to the hidden C target, that is,

$$VE_{68} = AR_{VOL} - AR_{C68}\,, \tag{7.5}$$

$$VE_{16} = AR_{VOL} - AR_{C16}\,, \tag{7.6}$$

$$VE_{5} = AR_{VOL} - AR_{C5}\,, \tag{7.7}$$

$$VE_{0} = AR_{VOL} - AR_{C0}\,, \tag{7.8}$$

where:

VE_{68}, VE_{16}, VE_{5} and VE_{0} are measures of memorised voluntary accommodation when the opaque mesh was placed at the individual dark focus level, using as baselines the responses to the C targets with contrasts of 68%, 16%, 5% and 0% respectively;

AR_{VOL} is the average of the median accommodation responses in the two voluntary trials when the opaque mesh was placed at the individual dark focus level;

AR_{C68}, AR_{C16}, AR_{C5} and AR_{C0} are the median accommodation responses in the respective second trials when the C target was viewed alone, for C target contrasts of 68%, 16%, 5% and 0% respectively.

Principal axis regression was used to calculate best fitting lines to the plots of Mandelbaum effect as a function of voluntary error.[7] However, confidence intervals for the slopes of these lines were not calculated due to the small sample size.

I investigated the effects of contrast on the Mandelbaum effect using post hoc comparisons after a Friedman test (see section C.3).

7.3. Results

Individual Subjects

The accommodation response to the C target with mesh interposed seems to increase as contrast is lowered for two of the subjects (Subjects B & I), but not for the other two subjects (Subjects D & Q) (see Figures 7.2 & 7.3). It is difficult to determine by observation whether or not the Mandelbaum effect becomes larger with poorer target contrast. The accommodation responses to a non-existent target (i.e. 0% contrast C target) are not very different from the responses to the high contrast (68%) C target.

Relationship between Voluntary Ability and the Mandelbaum Effect

Both the Mandelbaum effect and voluntary ability show little variability between subjects in this study (Figure 7.4). The slopes of the best fit lines to plots of Mandelbaum effect as a function of voluntary error may become more positive with lower contrast targets (Figure 7.4, Table 7.1), although this observation was not tested formally due to the small number of subjects.

Magnitude of the Mandelbaum Effect and Voluntary Ability

There is not a significant Mandelbaum effect for any of the distant targets (Table 7.2). Even with an invisible (0% contrast) distant target, the mesh target is not able to draw accommodation inward to give a greater Mandelbaum effect. The values of the Mandelbaum effect differ little between subjects (Table 7.2), the same as it was in the previous study (see Table 6.1).

Subject Perceptions

The subjects' responses to the question 'How did the target appear? Was it blurred or clear?' are summarised in Table 7.3. The subjects' responses to the question 'What were you trying to do while looking at the target?' are summarised in Table 7.4.

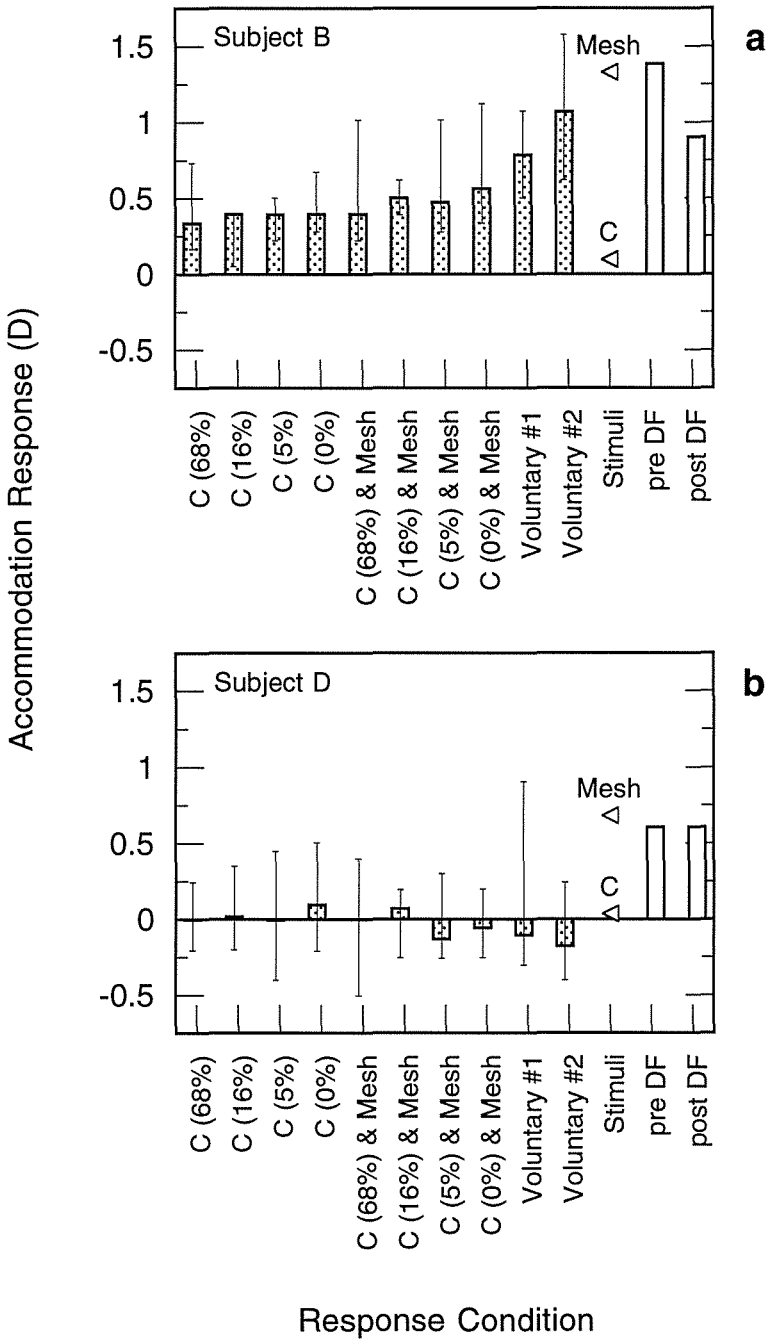


Figure 7.2. Accommodation responses of (**a**) subject B and (**b**) subject D, for distant C targets of various contrasts, with or without an interposed mesh, and responses on two trials when attempting voluntary accommodation to the hidden distant target. The median accommodation responses are plotted for the various conditions. Error bars denote the total range of response values for these subjects. Triangles denote the stimulus levels of the distant C target and the mesh target. Pre- and post-task dark focus levels are also shown.

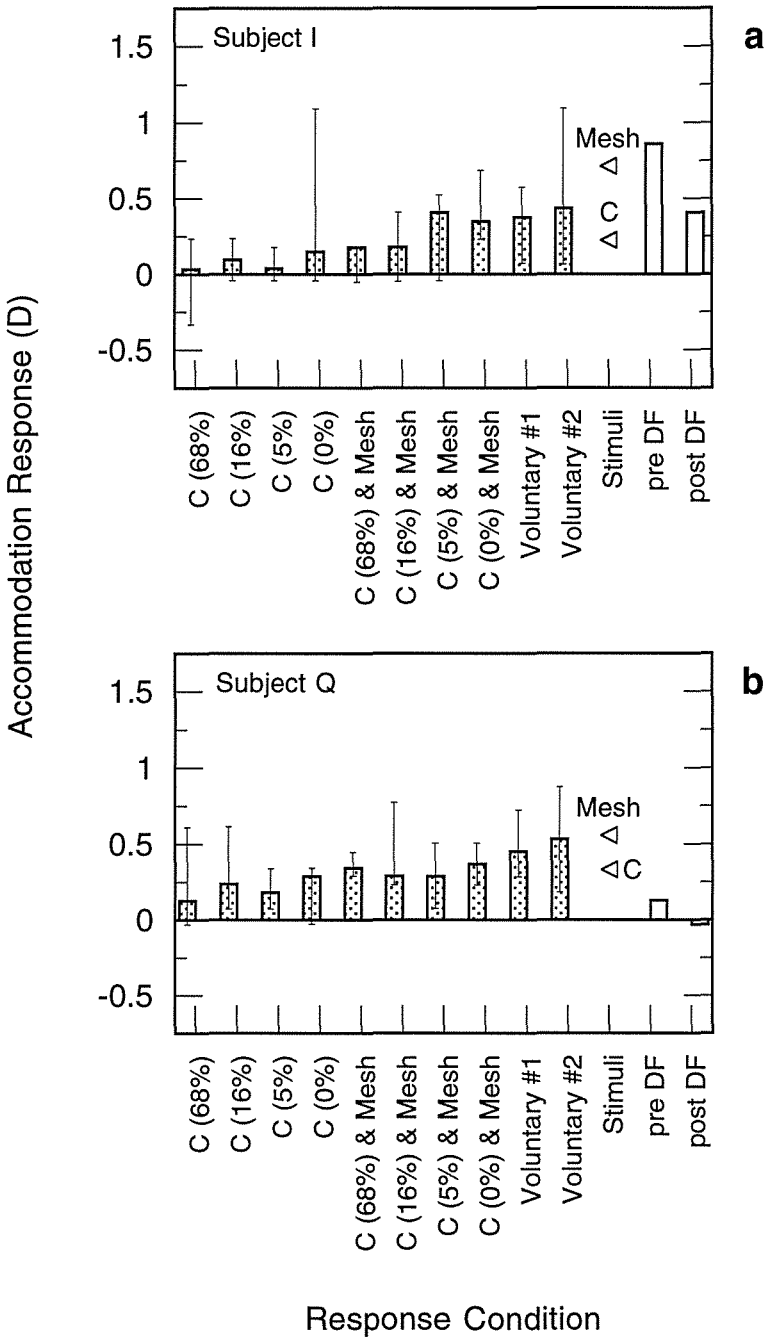


Figure 7.3. Accommodation responses of (**a**) subject I and (**b**) subject Q, for distant C targets of various contrasts, with or without an interposed mesh, and responses on two trials when attempting voluntary accommodation to the hidden distant target. Other details are as for Figure 7.2.

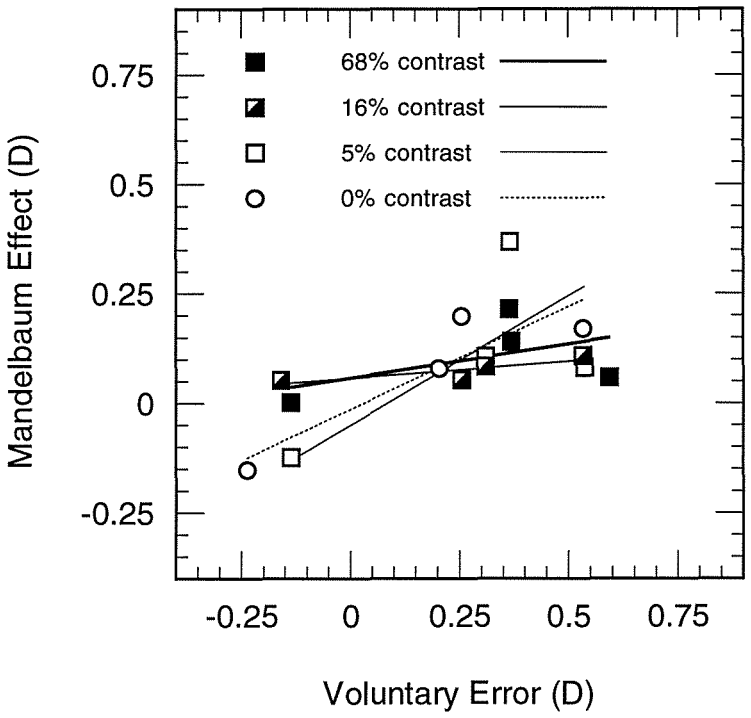


Figure 7.4. Mandelbaum effect as a function of voluntary error for distant C target contrasts of 68%, 16%, 5% and 0%. Solid and dotted lines are principal axis regression lines. The Mandelbaum effect is the median response to the C target and mesh combination minus the median response to the C target alone. The voluntary error is the median response when attempting voluntary accommodation to the hidden C target minus the median response to the C target alone. See the text for details.

7.4. Discussion

Effect of Contrast on the Mandelbaum Effect

In this study, the Mandelbaum effect was not significantly different from zero for all target contrasts (Table 7.2). Even reducing the distant target contrast to 0% did not lead to a significant Mandelbaum effect. There are a number of possible explanations for these findings. Firstly, the subjects may have been able to discern fine textural detail in the card on which the distant target was printed. Perhaps they used these fine contrast changes when the contrast of the C target was too low to be seen. However, if these cues were

Table 7.1. Parameters of best fit lines to plots of the Mandelbaum effect as a function of the voluntary error

C Target Contrast (%)	*Parameters of best fit equation* ($ME = b.VE + a$)	
	b	*a*
68	0.15	0.06
16	0.08	0.06
5	0.59	-0.05
0	0.47	-0.01

Best fit lines were calculated using principal axis regression.

Table 7.2. Summary of the Mandelbaum effect and dark focus values ($n = 4$)

Parameter	*Accommodation Value (D)*			$\hat{\psi}$*
	Mean	*Min.*	*Max.*	
Mandelbaum effect (68% contrast C)	0.10	0.00	0.21	5.4
Mandelbaum effect (16% contrast C)	0.07	0.05	0.11	4.4
Mandelbaum effect (5% contrast C)	0.11	-0.12	0.37	7.9
Mandelbaum effect (0% contrast C)	0.07	-0.15	0.20	4.7
Mean Dark Focus	0.61	0.05	1.14	-

* $\hat{\psi}$ is the test statistic for post hoc comparisons following the Friedman test (see section C.3). None of the Mandelbaum effect values were significantly different from zero at the 5% level, for which the critical value of the test statistic was 19.5.

Table 7.3. Selected subject observations when viewing the C target alone, the C target with mesh interposed, or when attempting voluntary accommodation

Subject Observation	*Proportion Subjects (/4)*		
	C target	*C & Mesh*	*Voluntary*
I. Changes in perceived size & distance			
1. Mesh on top of C & both at the same distance. This distance:			
a. unspecified		1	
b. at known distance of C		1	
2. C closer than mesh and vice versa alternately		1	
3. C appears closer than card on which it is printed	1		
4. Mesh appears closer than card on which it is printed			1
II. Other observations			
5. Fading of target	1	2	

Note that subjects could report more than one action per condition, so the columns do not necessarily total to four.

available then they would have been a very poor competitor against the sharp, high contrast detail of the interposed mesh target. The edge of the white distant target (4.8° eccentricity when fixating centrally) may have provided a peripheral stimulus to accommodation (section 1.5.4), but this peripheral stimulus would have been a poor competitor to the sharp central detail of the interposed mesh.

Another explanation for the lack of significant Mandelbaum effects is that perhaps the subjects of this study were using memorised voluntary accommodation to focus for the low contrast distant targets. Finally, the subjects may have been using proximal cues provided by the distant target and its relationship to other objects in the laboratory. They may have used these proximal cues to overcome the unwanted response to the strong blur cues provided by the interposed mesh target.

Table 7.4. Self reported actions when viewing the C target alone, the C target with mesh inter-posed, or when attempting voluntary accommodation

Category of Attempted Action, or Actual Action	*Proportion Subjects (/4)*		
	C target	*C & Mesh*	*Voluntary*
I. Indeterminate			
1. Nothing special	2		
II. Not related to targets			
2. Could not do anything (0% contrast C target)	1		
III. Related to C target			
3. Look at C, concentrate on C	3	3	
4. Focus on C	1	1	
5. Look at the distant card (0% contrast C target)	2	1	
6. Focus on imaginary letter (0% contrast C target)		1	
IV. Related to Mesh			
7. Ignore/don't concentrate on mesh			1
8. Look through/behind mesh		2	3
9. Focus further than mesh			1

Note that subjects could report more than one action per condition, so the columns do not necessarily total to four.

It may be that the perceived distance of the distant C target (regardless of its adequacy as a stimulus to blur-driven accommodation) provided a sufficient stimulus to accommodation to overcome the blur and proximal cues provided by the interposed mesh target. However when viewing the opaque mesh target, the central blur cues provided by this mesh overpowered the proximal cues to the distance of the C target available from the peripheral field of view.

In real world situations such as driving cars or piloting aircraft, interposed detail on windscreens has the potential to induce an inward shift

of accommodation. However, the relative strengths of proximal and blur stimuli can vary from situation to situation. For example, while driving a car in daylight there are usually many distance cues available in the outside scene that can provide a proximal stimulus to accommodation. However there may not be reliable distance cues available to a pilot making a landing approach to a runway at night. The findings of this study suggest that the Mandelbaum effect will be small provided there are sufficient proximal stimuli to the accommodation system, even though the target of interest is of poor contrast in comparison to some interposed detail.

If there are few proximal cues to accommodation then the accommodation response would reflect the relative strengths of the blur stimuli provided by the various targets, as was found by Benel using targets presented in a Badal stimulus system.[4] Benel found that low contrast grid targets were less able to induce a Mandelbaum effect than high contrast grid targets.

Relationship between the Mandelbaum Effect and Memorised Voluntary Accommodation

There may be changes in the relationship between the Mandelbaum effect and memorised voluntary accommodation with the contrast of the distant target (Table 7.1). The slopes of the best fit lines to these plots may increase with poorer contrast, but the small number of datum points prevent the slopes from being determined with an adequate degree of confidence.

Subject Perceptions

One subject in this present study (subject I) noted changes in the perceived distance of the targets during the Mandelbaum effect condition. In addition this subject also noted in some trials that the C target or the mesh target appeared to be closer than the card on which it was printed. Changes in perceived size and distance of the targets were noted by a number of subjects in the previous study (Table 6.3), and these are more fully discussed in Chapter 6.

A note should be made of the subjects' focusing strategies when viewing distant targets below their contrast thresholds. One subject reported that he could not do anything when viewing the 0% contrast distant C target (Table 7.4, category 2). Two subjects said that they simply looked at the card on which the C's were printed (Table 7.4, category 5). Finally, one subject attempted to focus on an imaginary letter (Table 7.4, category 6).

7.5. Summary

1. The study of Chapter 6 found that the Mandelbaum effect was not significantly different from zero for the real space target of that study. This present study shows that this negative finding was not simply due to the characteristics of the target detail in that study. In this study there was no significant Mandelbaum effect even when the contrast of the distant target was low or zero. This suggests that subjects were using proximal cues provided by the distant targets in both studies to overcome unwanted accommodation responses to the interposed mesh targets.
2. It may be that if sufficient distance cues are available for a target of interest, then they can be used to overcome the unwanted accommodation response to conflicting target detail, even if the target of interest would otherwise provide a poor blur stimulus to accommodation.

References

1. Ciuffreda, K.J. and D. Rumpf. Contrast and accommodation in amblyopia. *Vision Res.* 1985, **25**(10), 1445–1457.
2. Owens, D.A. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980, **20**, 159–167.
3. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction*. Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
4. Benel, R.A. *Visual Accommodation, the Mandelbaum Effect, and Apparent Size*. PhD thesis. Urbana-Champaign: University of Illinois, 1979.
5. Peli, E. Contrast in complex images. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1990, **7**(10), 2032–2040.

6. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin*. 1972, **77**(1), 54–64.
7. Sokal, R.R. and F.J. Rohlf. *Biometry*. 2nd ed. San Francisco: W. H. Freeman, 1981. pp. 594–601.

Chapter 8

Modelling the Accommodation Response to Conflicting Targets

8.1. Introduction

My objective in this study is to model the accommodation response to conflicting targets. Contrary to previous research, I wish to show that accommodation responses to conflicting targets can be predicted (see section 1.8.1). I hypothesise that a number of factors may explain the widely different responses to conflicting targets reported in previous studies.

In this study I investigate whether the *upper blur threshold* and the prior *adapting level* have an influence on the accommodation response to conflicting targets. The *upper blur threshold* is the maximum amount of target defocus that can elicit an accommodation response. The prior *adapting level* is the accommodation response level that a person has maintained before suddenly viewing two or more conflicting targets. It may be that the

response to conflicting targets depends on the prior adapting level. A factor which I control, but do not investigate, is the *subject instructions*. I give the subjects an instruction that requires them to attend to one particular target of a conflicting target pair.

In this study I also develop three alternative control system models and compare their performances by determining which most accurately predicts subjects' responses to conflicting targets. The *averaging model* predicts that people focus between conflicting targets. The *gain suppression model* predicts that people ignore conflicting targets and focus for an attended target. The *intermediate resting position model* predicts that people focus for the target which allows a response closest to their resting state of accommodation.

Some Factors in the Accommodation Response to Conflicting Targets

An overview of previous studies of the accommodation response to conflicting targets shows that people vary in their responses to conflicting targets (for a review see section 1.8.1.2).[1-7] Studies have found subjects who focus: the target closest to their dark focus level;[4,5] the nearer of two targets;[5] the target with vertical detail;[5] positions between conflicting targets;[6] any target detail;[2] and the target of interest.[7] I hypothesise that a number of factors may explain the different responses to conflicting targets noticed in previous studies.

SUBJECT INSTRUCTIONS

While some studies either definitely[4,7] or probably[1,3,8] gave the subjects instructions to attend to one of two conflicting targets, other studies used instructions which allowed the subject to vary their attention between targets (see section 1.8.1.4).[4-6] In this study I used an instruction that requires subjects to pay attention to one particular target, and this may reduce the variability that is observed when people are allowed to attend to any target at will.

VOLUNTARY ACCOMMODATION

Previous research contains suggestions that voluntary accommodation helps to overcome the inappropriate accommodation response to a conflicting target (see section 1.8.1.4). Owens noted that his subjects had to make a 'continuous effort' to keep a desired target in focus.[4] Also, when presented with two targets that straddled the dark focus, Owens' subjects tended to focus back and forwards between the two targets in a cyclic manner. Finally, one subject in Owens' study improved with practice at a conflicting targets task.

THE UPPER BLUR THRESHOLD

The upper blur threshold is the maximum amount of target defocus that can elicit an accommodation response. If for some reason a target is beyond the upper blur threshold then I hypothesise that it cannot provide a conflicting stimulus to accommodation (see sections 1.4.3.1 & 1.8.1.4). The upper blur threshold depends on the spatial frequency content and contrast of a target, and also on whether proximal cues to accommodation are available (see section 1.4.3.1). Therefore it is necessary to measure the upper blur threshold for particular targets and in the particular situations where the targets are presented.

ADAPTING LEVEL EFFECTS

I hypothesise that the prior adapting level of accommodation affects the response to conflicting targets. For example, a subject may focus for the nearer target if they previously viewed a near target, or the subject may focus the more distant target if they previously viewed a distant target. This effect is hypothesised to occur because the relatively focused detail of one target 'captures' accommodation better than the blurred detail of another target (see section 1.8.1.4). Note that this hypothesised effect occurs even though the second target is within the upper blur threshold; that is, even though the second target by itself elicits an accommodation response.

Modelling the Accommodation Response to Conflicting Targets

Benel proposed using the accommodation stimulus–response function slope as a measure of a target's adequacy to induce a Mandelbaum effect.[3] Benel found that the stimulus–response function slope is small for low contrast targets, and that these low contrast targets are also unable to induce a Mandelbaum effect. Rosenfield and Ciuffreda concluded from their study that accommodation responses to a conflicting target pair cannot be predicted from a knowledge of the responses to the individual targets of the pair.[6]

In this study I develop three alternative control system models to predict the steady state accommodation responses to conflicting targets. I base these model on other recent models of the accommodation response to single targets.[9,10]

ACCOMMODATION STRATEGIES WHEN PRESENTED WITH CONFLICTING TARGETS

The Averaging Model

The averaging model hypothesises that the accommodation response to two conflicting targets is an 'average' of the responses that would normally occur for individual targets. The response to the conflicting targets is weighted towards the target which provides the most effective stimulus.

Support for this model comes from the finding that there may be pooling of blur information to the accommodation controller over about the central 3° radius of the visual field (but see also Chapter 5).[11,12] It may be that the error signal to the accommodation controller is some sort of weighted average of blur inputs pooled over a small central portion of the visual field. Rosenfield and Ciuffreda found that many subjects focus between two conflicting targets,[6] and this would be consistent with the averaging model.

The Gain Suppression Model

The gain suppression model hypothesises that the accommodation response to two conflicting targets is simply the same as the response when viewing

the attended target by itself. In this model the conflicting target is completely ignored: it is as if the accommodation controller gain for the conflicting target has been reduced to zero, hence the name *gain suppression*.

This model is based on the observation that the Mandelbaum effect is very small in many subjects (see Chapters 6 & 7).[4] Possibly these subjects use voluntary accommodation to focus for an attended target. An inadequacy of the model is that it predicts *no* Mandelbaum effect rather than a *small* Mandelbaum effect.

The Intermediate Resting Position Model

The intermediate resting position model hypothesises that the accommodation response to two conflicting targets is the same as the response to the target which by itself gives a response closest to the individual resting position of accommodation. The other target is ignored.

This model is based on the studies of Owens[4] and Adams and Johnson[5] who found that many subjects focus for the target closest to their dark focus. There is a small difference between the conclusions of these studies and my model. Note that the intermediate resting position model in this study does *not* predict that a person will focus the *target closest to* their tonic accommodation level: the model predicts that a person will focus the *target that gives a response closest to* their tonic accommodation level.

8.2. Methods

Subjects

Thirteen subjects participated in the study and of these, two subjects were excluded. One subject was excluded because the central zone of his accommodation stimulus–response function was non-linear, and the other subject was excluded because he suffered from accommodative fatigue. The eleven remaining subjects were aged between 19 and 39 years. They were Q.U.T. Optometry School staff, postgraduate students and undergraduate students, and members of the public. Three subjects had extensive previous

experience in accommodation experiments, while eight subjects had some previous experience in accommodation experiments.

The subjects' right eye refractive errors ranged between -5.1 DS and +1.0 DS mean spherical equivalent, with cylindrical components less than 0.75 DC. Right eye visual acuities ranged between 6/3.8 and 6/6.

Apparatus

MODIFIED OPHTHALMETRON OPTOMETER AND BADAL STIMULUS SYSTEM

I measured accommodation responses from the subjects' right eyes with a modified Ophthalmetron optometer (see Appendix B & Figure B.1). The Ophthalmetron is an objective infra-red optometer that samples accommodation along the vertical meridian of the eye.

I presented targets to the subjects' right eyes in a twin-channel Badal stimulus system mounted on top of the Ophthalmetron (see Appendix B & Figures B.1, B.3). The targets in this study were presented on a white background in the Badal system at a luminance of about 40 $cd.m^{-2}$, sufficient for an accurate accommodation response.[13]

In this study subjects could not rely on proximal cues to accommodation because in the Badal system (assuming it is correctly aligned) target size and luminance do not change with stimulus level. Proximal cues may affect the accommodation response to conflicting targets (see Chapter 6), and in this study I used a Badal system to reduce their effects as much as possible.

The Badal stimulus system has an artificial pupil plane that is imaged at the subject's eye pupil (Figure B.3). In this study I placed a 5 mm pupil at the artificial pupil plane of the Badal system. I also placed cylindrical trial lenses at the artificial pupil plane to fully correct subjects' astigmatism (if present). One myopic subject (J) required a supplementary sphere at the artificial pupil to place his range of accommodation within the available stimulus levels provided by the Badal system. These lenses are imaged as if at the eye pupil.

CANON AUTOREF R-1 OPTOMETER

I used a Canon Autoref R-1 Optometer (see Appendix A) to measure the dark focus of accommodation. The Autoref is an objective infra-red optometer that allows the subject an open field of view through an infra-red reflecting beam splitter. I did not use the Ophthalmetron to measure the dark focus because it does not present a completely dark field to the subject.

TARGETS

I used two types of targets in this study. Subjects in Group 1 viewed bar targets ($n = 7$), while subjects in Group 2 viewed square grating targets ($n = 5$). (One subject viewed both bar and grating targets and was a member of both groups).

The bar target was 6° long and 2 minutes arc wide, high contrast black on white, photographed on Kodak Ortholith film. I made the target as thin as possible so that it would quickly lose contrast with defocus. In this way I hoped to decrease the upper blur threshold of accommodation for the target. I made vertical and horizontal versions of the bar target. I also made a 'cross' target by superimposing a vertical and horizontal bar in the same 35 mm transparency mounting. This target was required when the two conflicting bar targets were to be separated by 0 D. In actual fact, due to the thickness of the film, the two bars are separated by 0.03 D but this difference is negligible.

After running a number of subjects through the study with these bar targets it occurred to me that subjects may 'cheat' at the task by looking to one side of a conflicting target. Accommodation is poorer to a peripherally viewed target,[12] so a subject could look to one side of a conflicting target to enable a better response to an attended target.

To prevent subjects in Group 2 from viewing targets peripherally I made some square grating targets. The square grating was 6° square, composed of 2 minute arc strands separated by 6 minute arc gaps. The grating was high contrast black on white, photographed on Kodak Ortholith film. I made horizontal, vertical and 'cross' versions of the square grating just as I had for

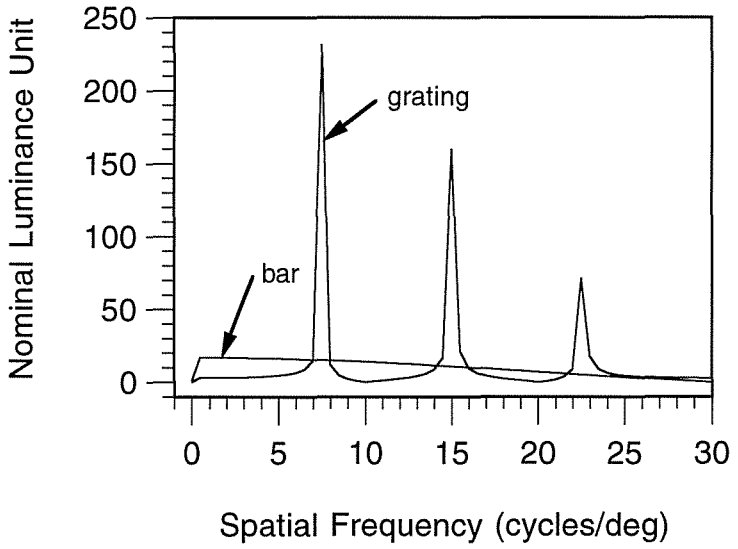


Figure 8.1. Theoretical Fourier spectra of the bar and square grating targets along a meridian perpendicular to the major axes of the bars. The bar target is 6° by 2 minute arc. The grating target has bars 6° by 2 minute arc separated by 6 minute arc gaps. See the text for details.

the bar target. When viewing the grating target, subjects were not able to view grating detail at any greater eccentricity than 3 minutes arc.

The bar target has a wide spatial frequency composition, while the grating target has peaks at 7.5 and 15 cycles.degree^{-1} (Figure 8.1).

Procedures

Each subject participated in four experimental sessions, except for one subject who missed session 4. One subject repeated Session 3 due to computer data loss.

SESSION 1

In Session 1, I performed an individual calibration of Ophthalmetron voltage output to subjective refraction (see section B.5). This was necessary to convert Ophthalmetron voltage output to an accommodation reading. I also performed a cycloplegic refraction on the subject's right eye and recorded visual acuity.

I then estimated subjective depth of focus for the vertical and horizontal targets used in the later main trials. I estimated depth of focus for all the subjects in Group 2 (who viewed the grating targets), but only for one subject in Group 1 (who viewed the bar targets). Accommodation in the subject's right eye was paralysed with 1 or 2 drops of cyclopentolate 0.5% or 1.0%. Subjective amplitudes of accommodation measured with a Rodenstock Hand Optometer (Rodenstock, Munich) ranged between 0.1 D and 1.5 D. The subject's left eye was patched, and the astigmatism in their right eye (if present) was corrected with a cylindrical trial lens at the artificial pupil plane of the Badal optical system (see Figure B.3). Note that the subjects viewed the targets in the Badal system through a 5 mm pupil placed at the artificial pupil plane of the Badal system.

I first estimated the position of best subjective focus for both the vertical and horizontal forms of the bar or grating target. I placed the target in Arm 1 of the Badal system (see Figure B.3) at a position well beyond the subject's far point, and then moved the target closer to the subject in 0.1 D steps. The subject's task was to report when the target first became blurred after it had been clear. I recorded the last position of clear focus before first blur. I also performed a trial with the target initially closer than the subject's far point and moving away from the subject. The order of these trials was counterbalanced.[14] I calculated the best focus position as the mean of the two blur threshold points, and then set the target at this best focus position. The reason for fixing the target at this position is that the depth of focus varies with mean defocus,[15,16] and a standard position is required for consistency.

I then determined the subjective depth of focus for the vertical and horizontal targets separately by oscillating the target in a sinusoidal motion at 1 Hz about the best focus position. I altered the amplitude of the sine motion in a staircase manner to determine the depth of focus, using both ascending and descending staircases. The amplitude of the sine wave could be altered in increments of 0.1 D. I had the subject listen to music in stereo headphones so that the faint sounds of the moving target could not be heard.

The subject's task was to report whether the clarity of the target was changing or not changing.

The subjective depth of focus was used in later control models. I used a depth of focus value of ±0.2 D for subjects in which the depth of focus was not determined experimentally. Campbell gave the depth of focus as ±0.2 D for a 5 mm pupil.[17]

SESSION 2

The purpose of the second session was to give the subject practice at focusing in the Badal system, to record the accommodation stimulus–response function, and to give the subject practice at focusing during a conflicting targets task.

Phenylephrine was instilled in the subject's right eye to dilate the pupil without affecting accommodation too greatly (see section 4.2). One drop of benoxinate 0.4% was instilled, followed a few minutes later by 1 or 2 drops of phenylephrine 2.5%. A protocol was used to exclude subjects susceptible to systemic or ocular side-effects of phenylephrine (see section 4.2). Phenylephrine was required for two reasons. Firstly, the Ophthalmetron optometer is sensitive to small pupils when they intersect the infra-red beam of the optometer (see section B.8). Secondly, the eye pupil had to be dilated to a size larger than the artificial 5 mm pupil in place at the artificial pupil plane of the Badal system. Right eye pupil sizes in Session 2 ranged between 4.5 mm and 8.0 mm.

The subject was given informal practice at focusing for targets in the Badal system. They focused for steady targets at various stimulus levels and also for step changes in target stimulus level. This practice session was necessary to ensure that the subjects could focus for Badal targets (see Chapter 3).

The accommodation stimulus–response function was then recorded for both horizontal and vertical targets separately. The subject's left eye was patched, and the astigmatism in their right eye (if present) was corrected with a cylindrical trial lens at the artificial pupil plane of the Badal optical

system (see Figure B.3). I first made a rough estimate of the subject's far and near points in the Badal system. To record the stimulus–response function I presented some subjects with a slow ramp motion of the target over their estimated accommodation range. The target started beyond the subject's estimated far point and then moved at 0.2 $D.s^{-1}$ to a point closer than the estimated near point. I sampled the accommodation response at 10 Hz. For other subjects I presented a steady target to the subject at positions commencing from beyond their far point to closer than their near point at 0.5 D intervals. At each position I sampled the accommodation response at 5 Hz for 5 seconds. The latter method was an easier task for the subjects.

Subjects who viewed the bar targets were given the following instruction:

> Look at the line naturally, the same as you would when normally looking at a book or sign at the same distance. Look at the middle of the line.

Subjects who viewed the square grating targets were given the following instruction:

> Look at the grid pattern naturally, the same as you would when normally looking at a book or sign at the same distance. Pay attention to the grid pattern. Look at the centre of the grid.

At the end of the session the subject was given practice at focusing to conflicting targets. This was to familiarise them with the accommodation task in the two main sessions (Sessions 3 and 4). During these practice trials I did not give the subjects any verbal feedback regarding their responses.

SESSIONS 3 AND 4

The purpose of Sessions 3 and 4 was to record subjects' accommodation responses to various combinations of conflicting targets and to single targets. Sessions 3 and 4 were identical except that the order of the various conditions were different in the two sessions. I ran two sessions to assess the repeatability of accommodation responses to conflicting targets.

One drop of benoxinate 0.4% was instilled in the subject's right eye, followed a few minutes later by 1 or 2 drops of phenylephrine 2.5%. While the pupil was dilating, I recorded the subject's pre-task dark focus of accommodation with the Canon Autoref. (In three cases I recorded a post-task dark focus).

The subject sat in the completely darkened experimental room for 5 minutes to allow any possible tonic adaptation effects to subside.[18,19] Subjects were aware of the room length before dark adapting, and this has the potential to contaminate the dark focus level.[20,21] However the 3.8 m length of one laboratory and the 6.7 m length of another laboratory should have been long enough to prevent proximal accommodation from contaminating the dark focus measure.[22] After 5 minutes of dark adaptation I instructed the subject to 'look straight ahead towards the end of the room', and then took several readings of refractive error from the subject's right eye using the Autoref. (The room was still dark when I took the readings). Two dim peripherally located eye-front illuminating lamps were used intermittently to align the eye (see section A.1). The subject wore no refractive correction during measurements with the Autoref.

When the subject's right eye pupil had sufficiently dilated I commenced the main trials. Right eye pupil sizes ranged between 5 mm and 8 mm. The subject's left eye was patched and their right eye astigmatism (if present) was corrected with a cylindrical trial lens at the artificial pupil plane of the Badal optical system. A 5 mm pupil was also in place at this artificial pupil plane.

Each trial run was 40 seconds long, divided into a 20 second *adapting period* followed by a 20 second *viewing period*. An example of a trial is shown in Figure 8.2. A 20 second period was used for the adapting and viewing periods to give a sufficiently representative sample of the steady accommodation response in both periods. During the adapting period the subject viewed the *adapting target*. For any particular subject, the adapting target was always vertical or always horizontal. In the viewing period the subject viewed an *attended target* by itself, or in most trials an *attended target*

and a *conflicting target*. The attended target was always the same orientation as the adapting target, and the conflicting target was always different from the attended target. Thus the subject's task was to always attend to a vertical target, or to always attend to a horizontal target. This was to avoid the confusion that might occur if during a trial the subject forgot to which target they should attend. In group 1, four subjects were instructed to always attend to a vertical bar, and three subjects were always to attend to a horizontal bar. In group 2, three subjects were instructed to always attend to a vertical grating, and two subjects were always to attend to a horizontal grating.

The various conditions were grouped in 6 series, represented schematically in Figure 8.3. In some trials the conflicting target was in front of the attended target, while in other trials it was behind the attended target. Sometimes the subject adapted at the same stimulus level as the attended target, while in other trials the subject adapted to the stimulus level of the conflicting target. In some trials there was no conflicting target.

In each series there were from 2 to 4 separations of the attended target and conflicting target. Maximum target separations ranged between 1.0 D and 4.5 D, and target separation increments ranged between 1.0 D and 1.5 D. All targets were presented within the linear region of the subject's accommodation stimulus–response function (see section 1.2.1). In this way it was possible to model individual subject's responses with a linear control system model, even though the subjects had different ranges of accommodation.

Altogether there were between 12 and 24 trials per experimental session depending on the size of the subject's stimulus–response function linear region. These trials were presented in counterbalanced order.[14] This is important because when initially presented with attended and conflicting targets in the viewing period, the subject *could not predict* the direction or magnitude of the necessary accommodation change. When the Badal system light shutters (see Figure B.3) switched the subject's view from one target arm to the other there was an audible 'click'. Thus the subject had an

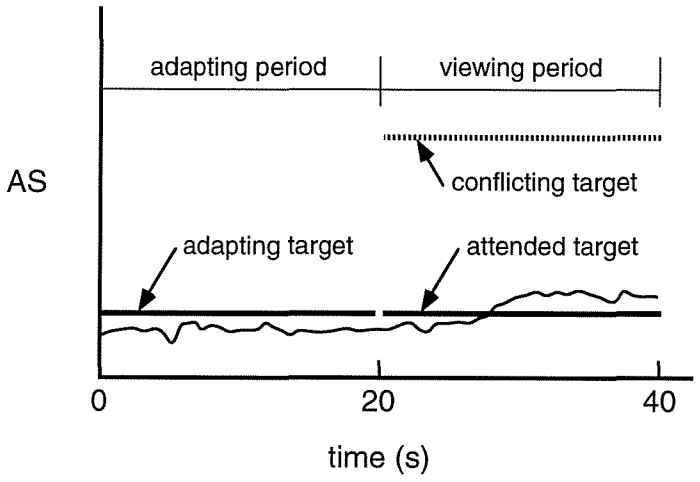


Figure 8.2. Schematic diagram of trials in sessions 3 and 4. Note that the levels of the adapting, conflicting and attended targets varied from one trial to the next. In some trials there was no conflicting target. The levels shown in this figure are only illustrative.

auditory cue that the targets had changed, but they did not know in advance which way they should focus.

Before commencing any trials I gave subjects information on the general nature of the trials, and also instructed them to perform a specific task, as in the following instructions. Subjects in Group 1 (bar targets) were instructed:

> First you will see a $\left\{\begin{matrix}\text{horizontal}\\ \text{vertical}\end{matrix}\right\}$ line. Look at the line naturally, the same as you would when normally looking at a book or sign at the same distance. Look at the middle of the line. Later the computer will show you two crossed lines. When this happens keep looking at the $\left\{\begin{matrix}\text{horizontal}\\ \text{vertical}\end{matrix}\right\}$ line. One or both of the lines may be blurred at first. Look in the direction of the intersection of the two lines, but always concentrate on the $\left\{\begin{matrix}\text{horizontal}\\ \text{vertical}\end{matrix}\right\}$ one, and ignore the other line.

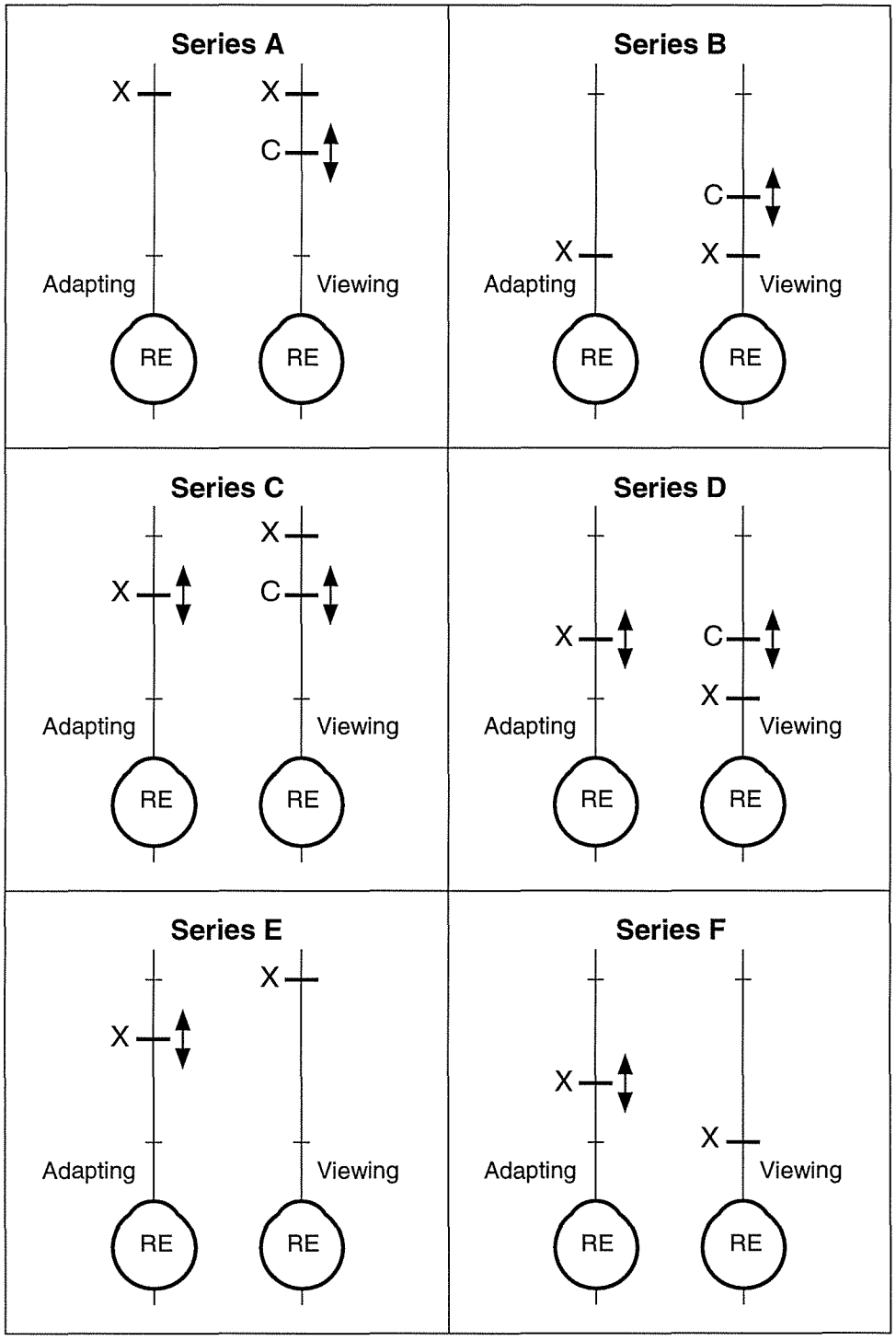


Figure 8.3. Schematic diagram of the six trial series. The target to which the subject must attend is marked by an X. In the adapting period the subject attends to the *adapting target* and in the viewing period to the *attended target*. The *conflicting target* is marked by a C. Target positions that vary from trial to trial are denoted by double-headed arrows.

Subjects in Group 2 (square grating target) were instructed:

> First you will see a {horizontal / vertical} grid. Look at the grid naturally, the same as you would when normally looking at a book or sign at the same distance. Pay attention to the grid. Look at the centre of the grid. Later the computer will show you two crossed grids. When this happens keep looking at the {horizontal / vertical} grid. One or both of the grids may be blurred at first. Look in the direction of the centre of the two grids, but always concentrate on the {horizontal / vertical} one, and ignore the other grid.

These instructions gave the subject a definite task to attend to one particular target — the adapting target in the adapting period, and the attended target in the viewing period.

During each 40 second trial I sampled the accommodation response at 40 Hz. Samples taken at 40 Hz from a model eye show a flat power spectrum plot in the 0–6 Hz frequency range (Section B.7). It was unreasonable to expect subjects to refrain from blinking for 40 seconds, so subjects were instructed to blink whenever necessary but, if possible, to space the blinks out over time. Spurious values in the accommodation records caused by blinks were later edited out manually.

Analysis

SESSION 1 DATA

Ophthalmetron Calibration Equation

I calculated calibration equations relating Ophthalmetron voltage output to subjective refraction for each subject. The theory and results are listed in section B.5.

Ocular Refraction

The subjective refraction was converted to an ocular refraction for infinite viewing distance and referred to an arbitrary entrance pupil 3.05 mm behind the corneal vertex (section E.2)

Subjective Depth of Focus

For the vertical and horizontal targets separately the depth of focus was calculated as the mean of 5 reversals of the ascending staircase and 5 reversals of the descending staircase.

SESSION 2

Accommodation Stimulus–Response Function

The stimulus to and response of accommodation were calculated using the equations of section E.3. I then plotted the accommodation response as a function of the accommodation stimulus and determined the linear range of the function by eye. (Note that the values for linear ranges given in this chapter are for the range of *stimuli* over which the response function is linear.) For data within the linear range I calculated the slope and intercept of the best fit line using linear regression. An example of a stimulus–response function is shown in Figure 8.4.

SESSIONS 3 AND 4

Dark Focus Measurements

The subject's dark focus was calculated using the equations given in section E.3.

Main Accommodation Trials

In each trial I calculated the stimulus levels of the adapting, attended and conflicting targets using the equations of section E.3. I also converted the Ophthalmetron voltage readings to accommodation response values (section E.3), and manually edited blinks from the accommodation recordings. I had to reject some trials due to spurious values caused by the pupil intersecting the infra-red beam of the Ophthalmetron (see section B.8).

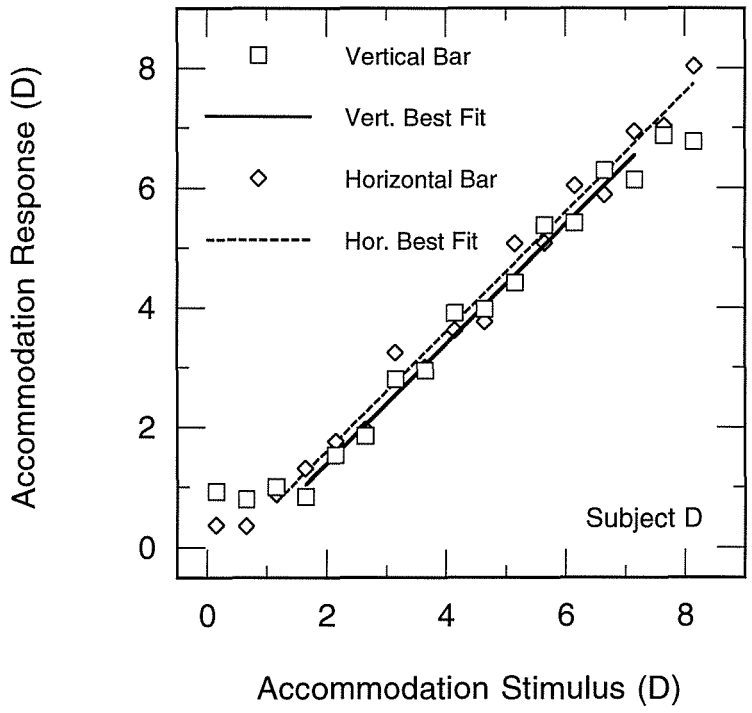


Figure 8.4. Accommodation stimulus–response function for subject D. The solid and dashed lines are best fit lines to the data for the vertical and horizontal bar targets respectively.

I then calculated various summary statistics for each trial. As a measure of the steady state response in the adapting period I calculated the median accommodation response (AR_{adapt}) in the last 12.8 seconds of the 20 second adapting period (Figure 8.2). This period was arbitrary but it did allow 7.2 seconds for the accommodation system to stabilise. As a measure of the steady state response in the viewing period I calculated the median accommodation response (AR_{view}) in the last 12.8 seconds of the 20 second viewing period.

DETERMINATION OF THE UPPER BLUR THRESHOLD

To determine the upper blur threshold I used the responses from Series F (Figure 8.3f). In Series F there was no conflicting target in the viewing period. Also, the attended target was at the same stimulus level as the adapting target or closer than the adapting target. The adapting period

response level was greater than the dark focus, so when initially presented with the attended target, the subject should have either focused to the attended target, or reverted to their dark focus level if the target was beyond the upper blur threshold. (For subjects A, D, and E the initial accommodation response at the end of the adapting was less than the dark focus by 0.2 D, 0.6 D, and 0.3 D respectively in one trial for each subject.)

I used the median response in the last 12.8 seconds of the viewing period as the dependent variable (AR_{view}). I then calculated the median accommodation response in the last 500 ms of the adapting period (AR_{ini}). I calculated the *initial accommodation error* (AE_{ini}) as the accommodation response in the last 500 ms of the adapting period (AR_{ini}) less the stimulus level of the attended target (AS_{attend}), that is,

$$AE_{ini} = AR_{ini} - AS_{attend} \; . \tag{8.1}$$

A plot of AR_{view} as a function of AE_{ini} should show a sharp drop in AR_{view} where the initial accommodation error is greater than the upper blur threshold.

ADAPTING LEVEL EFFECTS

To test whether an adapting stimulus affects the response to conflicting targets I compared the responses in Series A, C and E, and separately the responses in Series B, D and F.

There are attended and conflicting targets in both Series A and C, and in both series the conflicting target is coincident with the attended target or closer than the attended target (Figures 8.3a,c). So in the viewing period the target configurations in Series A and C are identical for a given separation of the two targets. The only difference between the two series is that in Series A the subject adapts at the stimulus level of the attended target, but in Series C the subject adapts at the stimulus level of the conflicting target. The responses in Series E are controls for those in Series A and C, that is; in Series E the subject must change focus from the level of the adapting target to the level of the attended target, but there is not a conflicting target present.

Similarly for Series B and D, there are both attended and conflicting targets in the viewing period (Figures 8.3b,d). In Series B and D, the conflicting target is coincident with the attended target or further than the attended target. In Series B the subject adapts at the stimulus level of the attended target, but in Series D the subject adapts at the stimulus level of the conflicting target. Series F acts as a control for Series B and D.

For each separation of attended and conflicting target I calculated the *adapting level effect* (ALE). For the Series C, A and E comparison the ALE is the difference between the Series C and A responses controlled for the Series E responses, that is,

$$ALE_{cae} = \left(AR_{view,c} - AR_{view,a}\right) - \left(AR_{view,e} - AR_{view,e'}\right) . \qquad (8.2)$$

$AR_{view,c}$, $AR_{view,a}$ and $AR_{view,e}$ are the median accommodation responses in the last 12.8 seconds of the viewing periods of the respective Series C, A and E trials. $AR_{view,e'}$ is the median accommodation responses in the last 12.8 seconds of the viewing period of the Series E trial where the adapting and attended targets are at the same level. The parameters in the second set of brackets of equation (8.2) control for the effect of prior adapting level on the responses to *single* targets. For the Series C versus A comparison, a positive value of ALE indicates the presence of an adapting level effect to conflicting targets.

A similar equation was used for Series B, D and F comparisons:

$$ALE_{dbf} = \left(AR_{view,d} - AR_{view,b}\right) - \left(AR_{view,f} - AR_{view,f'}\right) . \qquad (8.3)$$

This time a negative value of ALE indicates the presence of an adapting level effect. This is because in Series D the adapting level is lower than in Series B, and a Series D minus Series B difference will be negative if there is an adapting level effect.

HISTOGRAM INFORMATION ON THE RESPONSES TO CONFLICTING TARGETS

For each trial I calculated histograms of accommodation response values in the last 12.8 seconds of the adapting period, and also in the last 12.8 seconds of the viewing period. The frequency distributions have a bin width of 0.1 D.

Using the histogram information it is possible to determine where subjects focus in relation to two conflicting targets, and what percentage of time they spend at various focus positions. However I did not compare the histogram accommodation response values with the *target stimulus levels* because the results of this comparison can be misleading. For example, suppose that a subject accommodates by 4 D when viewing two targets, one target at 2 D and the other target at 6 D. The subject *is* focusing between the two targets, but is this because one or both of the targets are inducing a Mandelbaum effect? If the subject normally focuses by 4 D to the 6 D target then it is obvious that the target at 2 D has no effect on the subject's accommodation. Obviously, the response to a conflicting target pair must be compared to the responses to the individual targets of the pair.

In this study, I compared the histogram information in each trial to the *predicted responses* to the attended and conflicting targets. I predicted the responses to the attended and conflicting targets using the stimulus–response function parameters of Session 2, that is, using the stimulus–response function slopes and intercepts. For each trial and each histogram bin accommodation value I calculated the difference of this bin value from the predicted responses to the attended and conflicting targets thus:

$$x = AR_{bin} - sAR_{attend}\ , \tag{8.4}$$

$$y = AR_{bin} - sAR_{conflict}\ , \tag{8.5}$$

where x is the difference of the particular accommodation response bin value (AR_{bin}) from the response to the attended target predicted from stimulus–response function parameters (sAR_{attend}), and where y is the difference of the particular accommodation response bin value (AR_{bin}) from the response to the conflicting target predicted from stimulus–response function parameters($sAR_{conflict}$). In other words, the parameter x is the difference of the

actual response from the predicted response to the attended target, and the parameter y is the difference of the actual response from the predicted response to the conflicting target. I collated all these x and y values and their associated frequencies and, for each subject, plotted y as a function of x for all trials in Series A, B, C and D. I did not use Series E and F because there was no conflicting target in these series.

Control System Models

MODEL CONFIGURATION

I developed a control system model to test the three hypothesised patterns of responses to conflicting targets. I used variants of the control model to represent different features of the three hypothesised response patterns. Although these models are dynamic it should be noted that they were only developed to model the static accommodation response.

Averaging Model

The averaging model hypothesises that the accommodation response to two conflicting targets is an 'average' of the responses that would normally occur for individual targets.

The control system model has two accommodation stimuli as inputs (AS1, AS2) and the accommodation response (AR) as the output (Figure 8.5a). The accommodation errors in each channel are obtained by subtracting the accommodation response (AR) from the respective accommodation stimuli (AS1, AS2). The accommodation error represents the amount of blur at the retina due to incorrect focus. The sign of the accommodation error is signalled by chromatic aberration,[23] and possibly other cues such as astigmatism and fluctuations of accommodation (see section 1.4.1.2). Note that in this control model the sign of the accommodation error indicates the direction in which the response must go to correct the error. For example, if the stimulus is at 6 D and the response is at 4 D, then the accommodation error in the model is +2 D.

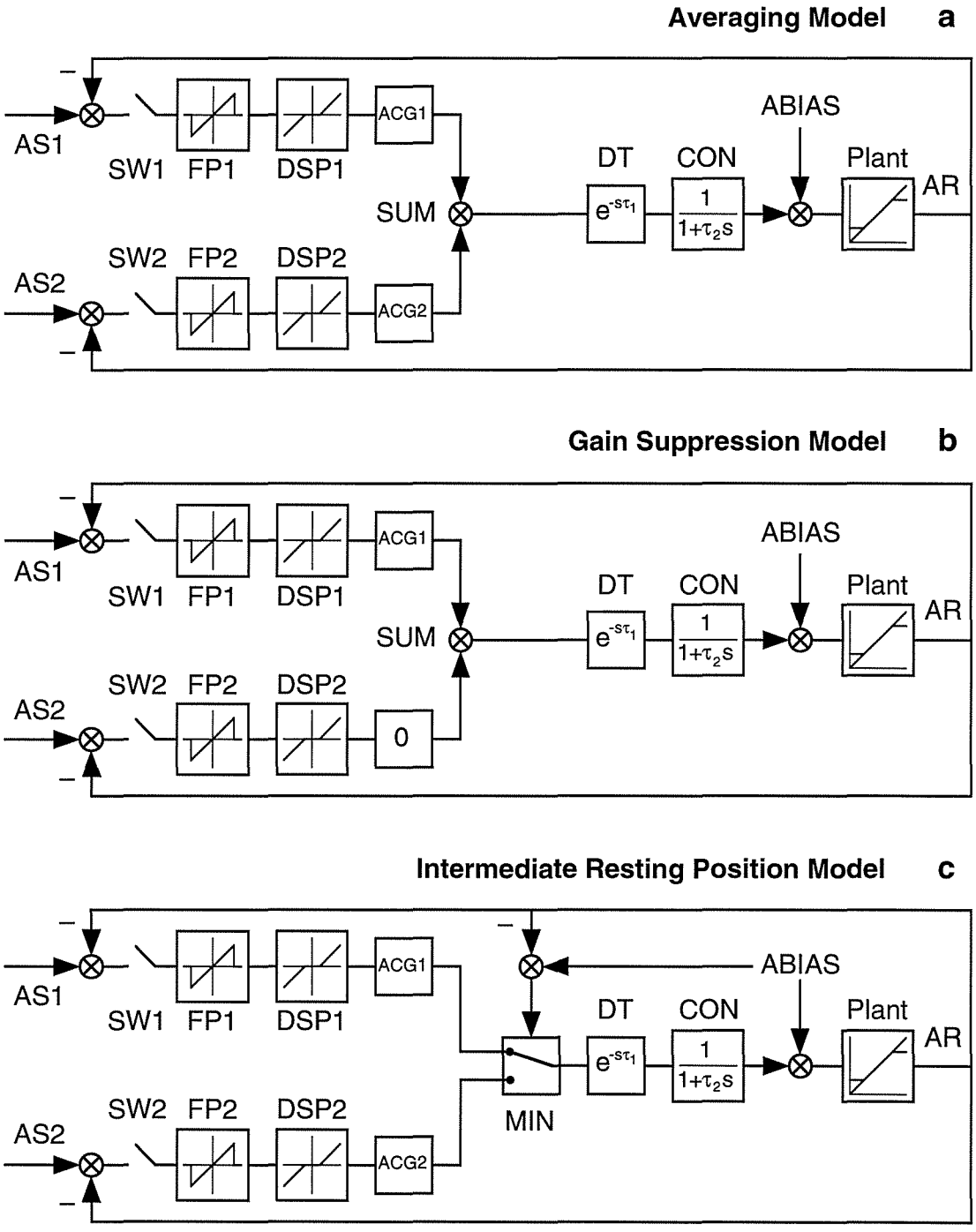


Figure 8.5. Control models of accommodation. The model components and signals are: accommodation stimuli (AS1, AS2); switches (SW1, SW2); fine pass filters to model upper blur thresholds (FP1, FP2); dead space elements to represent depth of focus (DSP1, DSP2); proportional controllers (ACG1, ACG2); summing junction (SUM); dead time element (DT); phasic controller (CON); accommodation resting level (ABIAS); accommodation plant (Plant); and accommodation response (AR). τ_1 = 350 ms. τ_2 = 6 s. Table 8.2 lists the values of other parameters.

Switches (SW1, SW2) are opened to represent the absence of a target or closed to represent the presence of a target.

The upper blur thresholds of accommodation for the respective targets are represented by fine pass filters (FP1, FP2). The output of these filters is equal to the accommodation error input when the accommodation error is smaller than the upper blur threshold. However, the output of the filters is zero when the accommodation error is greater than the upper blur threshold. The upper blur threshold for the attended target was determined experimentally for the subjects in this study. It was assumed that the upper blur threshold is the same for the attended and conflicting targets.

The depth of focus of the eye for the respective targets are represented by dead space elements (DSP1, DSP2). When the accommodation error is within the depth of focus the output of the dead space element is zero, otherwise the output is reduced by half the depth of focus. (For example if the subjective depth of focus is ±0.3 D, then the output of the dead space element is zero for inputs in the range -0.3 D through +0.3 D, otherwise the output is reduced by 0.3 D. If the input to the DSP element was +0.4 D, then the output would be +0.1 D because 0.3 D of the 0.4 D of defocus is not perceptible by the accommodation system.) This element represents the inability of the eye to respond to small amounts of blur. For some of the subjects I determined the subjective depth of focus experimentally, while for other subjects I used a value of ±0.2 D from the literature representative of a 5 mm pupil.[17]

The accommodation controller gains (ACG1, ACG2) are proportional controllers that give the stimulus–response function a slope less than unity. This results in the classic lead of accommodation for targets further than the resting position, and a lag of accommodation for targets closer than the resting position.[12] The controller gains were determined by varying them in a trial-and-error manner to match the model output with the actual stimulus–response function (see next section).

An important feature of the model is the summing junction (SUM) after the two proportional controllers. This element represents the pooling of blur information from the two targets to the accommodation controller.

The dead time element (DT) is shown in Figure 8.5a in Laplace notation. It represents the neural conduction time of the afferent and efferent accommodation neural pathways as well as latencies in the ciliary body and lenticular apparatus. I used a literature value of 350 ms for the dead time (τ_1).[24] Hung *et al.* split the dead time into controller delay and plant delay,[25] but, for simplicity, I placed all the delay at the controller. The differences in the steady state are probably negligible.

The phasic controller (CON) is a first order element, and is shown in Figure 8.5a in Laplace notation. Together with the proportional gain terms ACG1 and ACG2, the controller forms a leaky integrator. Krishnan and Stark demonstrated that, unlike pure proportional and integral controllers, the leaky integrator accounts for the slow drift of accommodation towards its resting level when a subject views an empty field after first viewing a target.[26] I could not measure the time constant of (τ_2) the controller experimentally because I could not present a completely empty field to the subjects in the Badal optical system. Instead I used a value of 6 seconds for the controller time constant which is consistent with the open-loop responses in other studies.[18,26] Hung and Semmlow demonstrated that a combination of a gain element and first order element acts in the steady state as a proportional controller.[9] I did not include a tonic controller[10,27] in the model because I could not present subjects with empty fields in the Badal optical system, and hence could not determine the characteristics of their tonic adaptation. Tonic adaptation may have been occurring over the 40 second period of each trial.[19]

The tonic resting level of accommodation is represented in the model by ABIAS. I used the subject's dark focus as an estimate of the tonic resting level.

The final element in the model is the plant which represents the lens and ciliary body. The inability of the eye to relax accommodation beyond the far

point or to increase accommodation beyond the near point are modelled as saturation limits. (Note that the far point in an eye with intact accommodation can be more myopic than the true cycloplegic far point.[28]) If the subject's stimulus–response function showed a definite near point or far point I included these points in the model. These far and near point parameters probably made little difference to the steady state response, because targets were always presented within the near and far points. The ciliary body and lens could have been represented by a separate controller,[29] but for simplicity I modelled the plant simply as a unit gain element with saturation limits.

Gain Suppression Model

The gain suppression model hypothesises that the accommodation response to two conflicting targets is simply the same as the response when viewing the attended target by itself.

The gain suppression control model is very similar to the averaging control model (Figure 8.5b). However in the gain suppression model, one stimulus (AS1) is the attended target, and the gain element (ACG2) for the ignored target (AS2) is set to zero. The second target (AS2) is as if it were absent. Gain suppression is obtained by voluntary effort, attention, concentration or some higher order process.

The Intermediate Resting Position Model

The intermediate resting position model hypothesises that the accommodation response to two conflicting targets is the same as the response to the target which by itself gives a response closest to the individual resting position of accommodation.

The intermediate resting position control model is similar to the averaging model (Figure 8.5c). However, the intermediate resting position model replaces the summing junction of the averaging model with a function (MIN) that switches to the target which gives a response closest to the resting position (ABIAS). The MIN function is not mathematically defined. Instead, it represents a process in which the subject attends to either

target and by a method of trial-and-error finds the target that gives a response closest to the tonic position (ABIAS). To implement the model I ran a trial with the switch of the MIN function set to receive a signal from one target, then ran the trial again with the switch set to the second target and, finally, chose the response (AR) that was closest to the dark focus.

MODEL IMPLEMENTATION

I implemented the control models with the Tutsim™ block diagram simulation language (Tutsim Products, Palo Alto, CA) on an IBM-PC clone. The model files are listed in section D.2.

Estimation of Accommodation Controller Gains

To estimate the accommodation controller gain for a particular target I used the gain suppression model (Figure 8.5b). I used literature values for the dead time (τ_1) and phasic controller time constant (τ_2). I used experimentally determined values for the dark focus (ABIAS) and plant saturation limits. I used either a literature value or experimentally determined value for the depth of focus (DSP1). No subjects showed a definite upper blur threshold, so fine pass limits were not included (FP1). This left only the accommodation controller gain (ACG1) to estimate.

I altered the controller gain (ACG1) by a trial-and-error method to match the modelled stimulus–response function with the actual stimulus response function. I did this separately for both vertical and horizontal forms of the target. I was able to model the stimulus–response function in 4 subjects from Group 1 (who viewed the bar targets), and in 3 subjects from Group 2 (who viewed the grating targets). For these subjects, the model stimulus–response function slopes were within -0.5% to 0.7% of the actual slopes (Table 8.1). The model stimulus–response function intercepts were within -1.1 D to +0.6 D of the actual intercepts. The other subjects in both groups had stimulus–response slopes close to or greater than +1 which I could not model without system instability. For one such subject (H) I tried adding a 1 Hz oscillation representing the fluctuations of accommodation,[25] but I had to increase the amplitude of the oscillations to unrealistic levels to achieve

Table 8.1. Adequacy of the control model to predict the accommodation stimulus–response function slopes and intercepts for single targets.

Group	*Subject*	*Target*	*Actual Slope*	*Model Slope*	*% error*	*Actual Intercept*	*Model Intercept*	*error (D)*
1	A	V	0.82	0.82	+0.2	+0.37	+0.07	-0.30
		H	0.87	0.87	+0.1	+0.01	-0.08	-0.09
	B	V	0.99	-	-	-0.75	-	-
		H	1.16	-	-	-1.40	-	-
	C	V	0.67	0.67	+0.2	+0.22	+0.54	+0.32
		H	0.82	0.82	+0.3	-0.30	+0.28	+0.58
	D	V	1.00	-	-	-0.62	-	-
		H	1.00	-	-	-0.40	-	-
	E	V	0.93	-	-	-0.08	-	-
		H	0.90	-	-	0.03	-	-
	F	V	0.75	0.75	+0.7	+0.54	+0.14	-0.40
		H	0.84	0.84	-0.5	+0.25	+0.08	-0.17
	G	V	0.75	0.76	+0.4	+0.95	-0.15	-1.1
		H	0.85	0.85	+0.1	+0.68	-0.17	-0.85
2	A	V	1.04	-	-	-0.16	-	-
		H	0.76	-	-	+0.29	-	-
	H	V	1.09	-	-	-0.68	-	-
		H	0.98	-	-	-0.35	-	-
	I	V	0.44	0.44	+0.1	+0.40	+0.27	-0.13
		H	0.51	0.51	+0.2	+0.09	+0.30	+0.21
	J	V	0.79	0.79	-0.3	+0.03	-0.22	-0.25
		H	0.87	0.88	+0.5	+0.06	-0.19	-0.25
	K	V	0.93	0.94	+0.5	-0.19	-0.12	-0.07
		H	0.87	0.88	+0.3	+0.12	-0.09	-0.20
1 & 2	mean				+0.2 %			-0.19 D
	max.				+0.7 %			+0.58 D
	min.				-0.5 %			-1.1 D

Group 1 subjects viewed a bar target and group 2 subjects viewed square grating targets. 'V' stands for the vertical target and 'H' for the horizontal target. The gain suppression model was used for each target separately. See Table 8.2 and Figure 8.5 for individual model parameters. Note that it may have been possible to model responses to some targets whose cells are left blank but this was not attempted if the response to the other target for that subject could not be modelled.

meagre improvements in the stimulus–response slope, and so abandoned this approach. The inability to model many normal subject's steady responses was frustrating, and it is an inadequacy of all recent control models of accommodation (see Discussion).

COMPARISON OF THE THREE MODELS OF RESPONSES TO CONFLICTING TARGETS

For each subject I used Tutsim™ to model each experimental trial with the three models — the averaging (ave) model, the gain suppression (gs) model, and the intermediate resting position (irp) model. For each modelled trial I calculated the mean accommodation response in the last 12.8 seconds of the adapting period (AR_{adapt}) and the mean response in the last 12.8 seconds of the viewing period (AR_{view}). This was to compare the modelled responses with the actual responses.

For each trial, I then calculated the change in response from the adapting period to the viewing period for the actual response and for the three modelled responses:

$$\Delta AR = AR_{view} - AR_{adapt} \ . \tag{8.6}$$

In each trial, and for each model I then calculated the model error as the ΔAR value predicted by the model less the actual ΔAR value, that is,

$$moderr = \Delta AR_{model} - \Delta AR_{actual} \ . \tag{8.7}$$

I also calculated the absolute values of these model errors. A good model should have absolute model errors that cluster close to zero.

8.3. Results

Subject characteristics and accommodation parameters are summarised in Table 8.2.

Upper Blur Threshold

To test for an upper blur threshold I used the responses from Series F (Figure 8.3f), and plotted the median response in the last 12.8 seconds of the

Table 8.2. Subject characteristics and accommodation parameters

Parameter	*Tgt**	*Subject*											
		Group 1†							*Group 2†*				
		A	*B*	*C*	*D*	*E*	*F*	*G*	*A*	*H*	*I*	*J*	*K*
Age (years)		39	24	19	21	21	34	21	39	22	23	20	23
±DSP‡	1	0.20	0.20	0.20	0.20	0.30	0.20	0.20	0.10	0.25	0.05	0.25	0.15
	2	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.20	0.25	0.30	0.10
Linear Range													
min.	1	0.2	1.7	0.5	1.7	0.9	0.4	0.6	1.2	1.7	1.9	1.8	0.9
max.	1	3.2	6.2	8.0	7.2	6.4	4.4	5.1	2.2	6.2	4.9	6.3	5.9
min.	2	0.7	1.2	1.5	1.2	1.9	0.4	0.6	0.7	0.7	1.9	2.3	0.4
max.	2	2.7	6.2	8.6	8.2	6.4	3.9	4.6	3.7	7.2	4.4	6.3	6.4
AS–AR Slope	1	0.82	1.16	0.67	1.00	0.90	0.75	0.85	1.04	1.09	0.51	0.87	0.93
	2	0.87	0.99	0.82	1.00	0.93	0.84	0.75	0.76	0.98	0.44	0.79	0.87
AS–AR Int.	1	0.4	-1.4	0.2	-0.6	0.0	0.54	0.7	-0.2	-0.7	0.1	0.1	-0.2
	2	0.0	-0.8	-0.3	-0.4	-0.1	0.25	0.9	0.3	-0.4	0.4	0.0	0.1
Attended Tgt		V	H	V	V	H	V	H	V	V	H	H	V
Target Range													
min.		1.2	1.7	2.7	1.6	1.8	1.6	2.0	1.3	1.8	1.9	2.8	1.6
max.		2.7	6.2	7.3	6.2	4.8	3.1	5.1	2.3	6.3	3.4	5.8	5.2
ACG	1	9.5	-	2.3	-	-	4.0	5.5	-	-	1.1	7.0	15.0
	2	8.0	-	6.0	-	-	9.0	3.1	-	-	0.8	3.8	7.0
Mean DF		0.5	0.4	1.6	1.2	1.7	0.7	-0.3	0.3	0.8	0.7	0.1	0.1
model ABIAS		0.5	-	1.6	-	-	0.7	0	-	-	0.7	0.1	0.1
Acc'n Far Pt		0.2	-	0.0	-	-	0.0	0	-	-	0.0	0.0	0.0
Acc'n Near Pt		3.3	-	8.0	-	-	4.8	5.7	-	-	3.5	6.7	6.6
		A	*B*	*C*	*D*	*E*	*F*	*G*	*A*	*H*	*I*	*J*	*K*

* Target 1 was the one used for the adapting and attended targets. Target 2 was the one used for the conflicting target. † Group 1 viewed bar targets and group 2 viewed square grating targets. ‡ A literature value of ±0.20 D for depth of focus was used for subjects A, B, C, D, F and G. *±DSP* is the depth of focus. *Linear Range* is the range of stimuli for which the stimulus–response function is linear. *AS–AR Slope* and *AS–AR Int.* are the slope and intercept respectively of the stimulus–response function. *Attended Tgt* is the direction of the adapting and attended targets. *Target Range* is the extent of stimulus levels presented to the subject in Sessions 3 & 4.

viewing period (AR_{view}) as a function of the initial accommodation error just before entering the viewing period (AE_{ini}). The final accommodation response was independent of the initial accommodation error for most subjects — some subjects were able to correctly focus for the target even when it was initially blurred by over 5 D (Figure 8.6).

Some representative response patterns are shown in Figure 8.6. One subject (A) in Group 1 possibly had an upper blur threshold of 1.5 D in the trials from one session, but this was not consistent over both sessions (Figure 8.6.e). For each subject I calculated the slope of the best fit line to the above functions using principal axis regression.[30] The slopes of the lines were not significantly different from zero for Group 1 ($t = 1.3$, $p > 0.05$, $n = 7$) or Group 2 ($t = 1.9$, $p > 0.05$, $n = 5$), indicating the lack of an upper blur threshold, at least for the range of representative initial blur levels in this study. (Some of subject G's Series F trials could not be used, limiting the range of initial blur levels.) Due to the absence of definite upper blur thresholds I did not use upper blur thresholds in the Fine Pass Filters of the control models (Figure 8.5).

Adapting Level Effects

The ALE is not significantly different from zero in either Group 1 or 2, for either the Series C, A and E comparison, or for the Series D, B and F comparison (Table 8.3). Furthermore, when the ALE is plotted as a function of the separation of the conflicting targets, the slopes of the best fitting lines are not significantly different from zero (Table 8.4). (Slope values were calculated using principal axis regression.[30]) This shows that the adapting level effect does not increase or decrease linearly with target separation.

I plotted the adapting level effect as a function of the separation of the attended and conflicting targets. Generally there are no obvious adapting level effects, although there are differences between subjects. Some subjects show an adapting level effect that increases with target separation (Figure 8.7d). Their accommodation response to a conflicting target pair is higher when they first adapt to a target at a higher stimulus level. Other

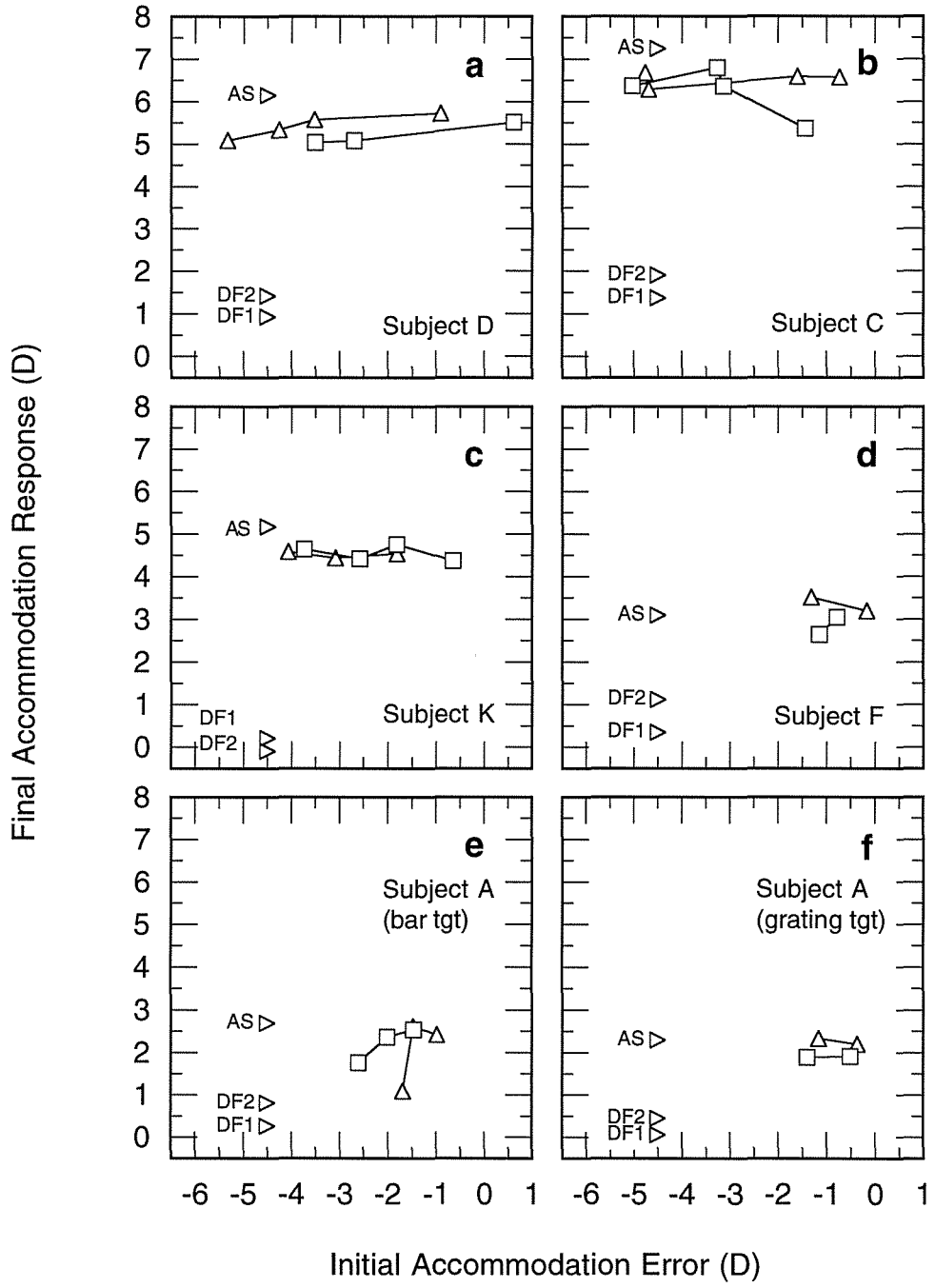


Figure 8.6. Upper blur thresholds. The accommodation response in the last 12.8 seconds of the viewing period of Series F is plotted as a function of the initial accommodation error for representative subjects. Negative values of initial accommodation error indicate an initial lag of accommodation. Responses in sessions 3 and 4 are denoted by squares and triangles respectively. Also plotted are the stimulus level of the attended target (AS) and the dark focus values in sessions 3 and 4 (DF1 and DF2 respectively).

Table 8.3. Summary of adapting level effects

Group*	*ALE (Adapting Level Effect in dioptres) †*					
	Series C, A & E			*Series D, B & F*		
	mean	*range*	*p (ALE ≠ 0)*	*mean*	*range*	*p (ALE ≠ 0)*
1 (n = 7)	0.04	-0.33 – +0.43	> 0.05	-0.12	-0.75 – +0.24	> 0.05
2 (n = 4)‡	-0.26	-1.59 – +0.22	> 0.05	-0.22	-0.43 – +0.05	> 0.05

* Group 1 viewed bar targets and Group 2 viewed square grating targets. † For a definition of the ALE see equations (8.2) & (8.3) and associated text. ‡ One subject from Group 2 was excluded due to insufficient data. The probability that the ALE is significantly different from zero was estimated with a t test.

Table 8.4. Summary of adapting level effect as a function of separation of conflicting targets

Group*	*slope of ALE (Adapting Level Effect in dioptres) as a function of separation of adapting and attended targets (dioptres)†*					
	Series C, A & E			*Series D, B & F*		
	mean	*range*	*p (slope ≠ 0)*	*mean*	*range*	*p (slope ≠ 0)*
1 (n = 7)	0.05	-0.41 – +0.68	> 0.05	0.736	-0.27 – +3.8	> 0.05
2 (n = 4)‡	0.07	-0.84 – +0.52	> 0.05	0.384	+0.02 – +0.89	> 0.05

* Group 1 viewed bar targets and Group 2 viewed square grating targets. † For a definition of the ALE see equations (8.2) & (8.3) and associated text. ‡ One subject from Group 2 was excluded due to insufficient data. The probability that the slope value is significantly different from zero was estimated with a t test.

subjects do not seem to be affected by the adapting level (Figures 8.7a,b). Some subjects show a higher adapting level effect for intermediate separations of the two conflicting targets (Figures 8.7e,f). In these subjects the adapting level effect is small for wide separations or narrow separations of the targets, but maximal for intermediate separations of the targets.

Two subjects (C, E) performed well on every trial bar one where the conflicting target captured their focus (Figures 8.8a,d). In one trial, subject C

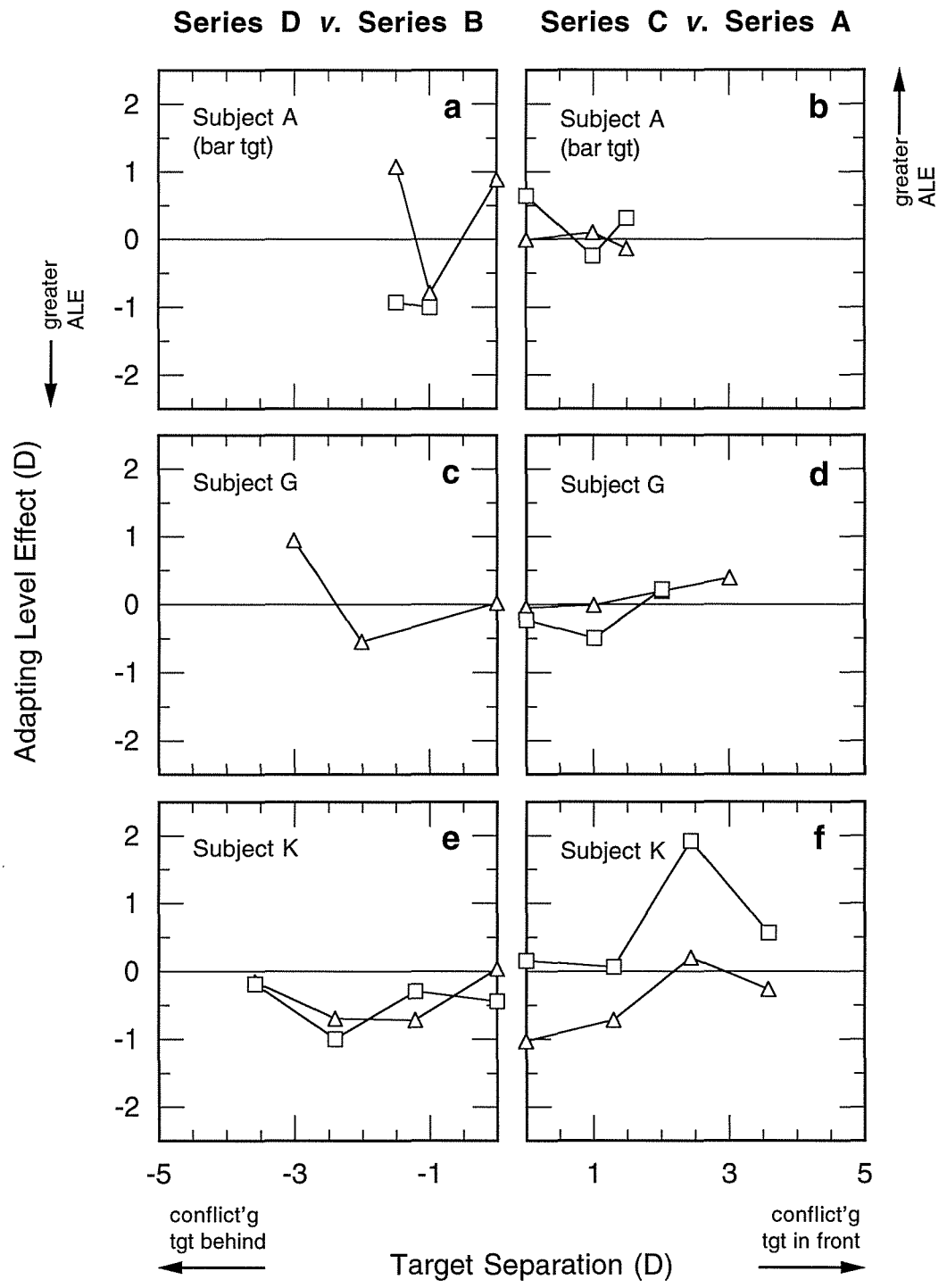


Figure 8.7. Adapting level effects (part 1). The adapting level effect (equations 8.2 & 8.3) is plotted as a function of the separation of attended and conflicting targets. Negative values of ALE indicate a greater effect for the Series D *vs* B comparisons. Positive values of ALE indicate a greater effect for the Series C *vs* A comparisons. Responses in Sessions 3 & 4 are denoted by squares and triangles respectively.

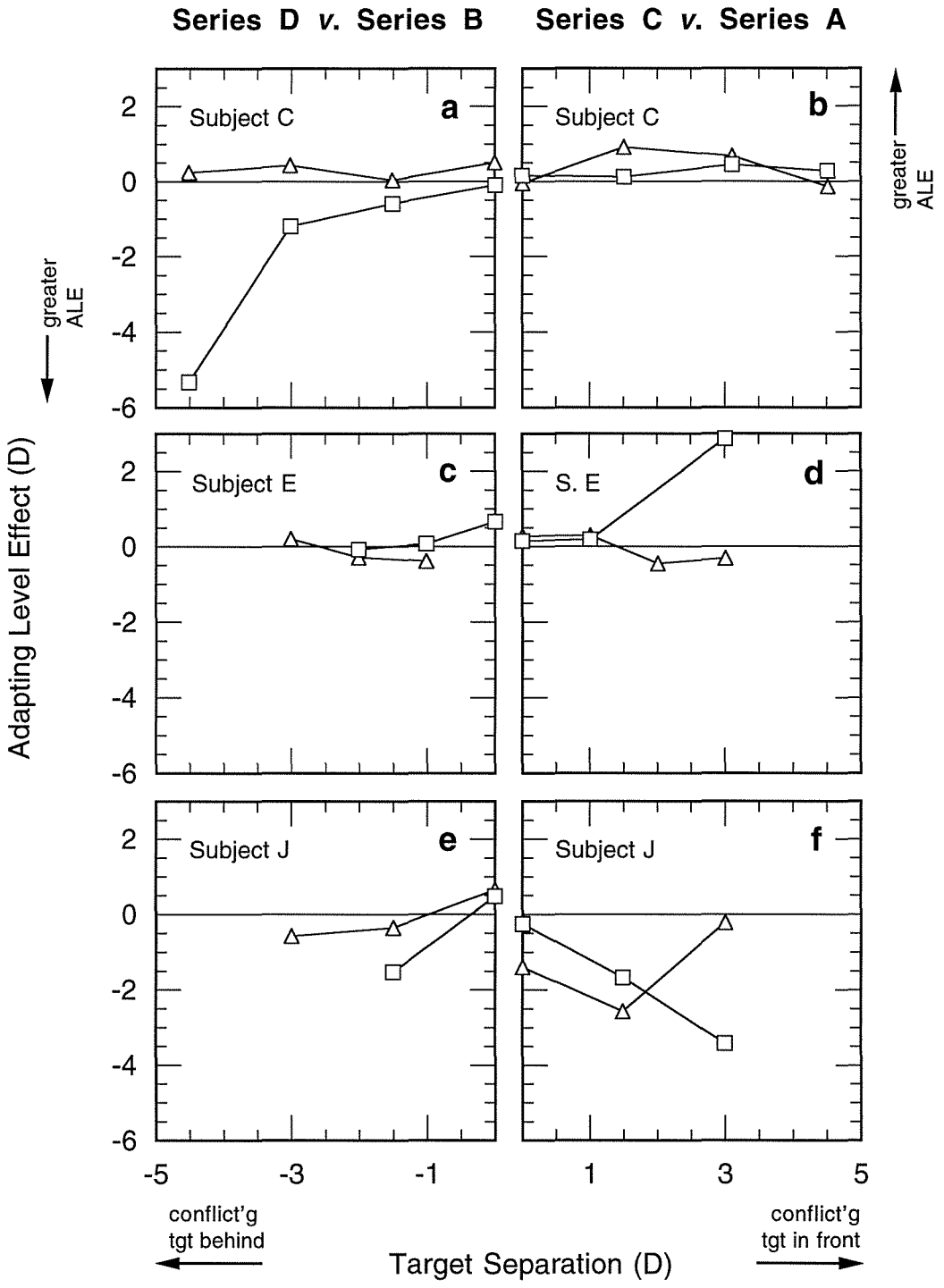


Figure 8.8. Adapting level effects (part 2). The adapting level effect (equations 8.2 & 8.3) is plotted as a function of the separation of attended and conflicting targets. Negative values of ALE indicate a greater effect for the Series D *vs* B comparisons. Positive values of ALE indicate a greater effect for the Series C *vs* A comparisons. Responses in Sessions 3 & 4 are denoted by squares and triangles respectively.

adapted at the level of the conflicting target and was not able to increase her accommodation to focus on the attended target (Figure 8.9a). Similarly, subject E was not able to relax her focus from the conflicting target towards the attended target in one trial (Figure 8.9b). Note that both subjects experienced this gross failure in only one of the two sessions — in the other session they were able to focus the attended target.

One subject (J) performed better at focusing to the attended target when a conflicting target was present than when the conflicting target was absent. In many of the Series E trials he failed to relax his accommodation (Figure 8.10). This caused the plot of ALE as a function of target separation to have a negative slope (Figure 8.8f). These effects are discussed later.

Histogram Information on the Responses to Conflicting Targets

I compared the subjects' accommodation responses in Series A, B, C and D to the responses predicted from the stimulus–response function parameters. The parameter x is the difference of the actual response from the predicted response to the attended target. The parameter y is the difference of the actual response from the predicted response to the conflicting target.

A plot of y as a function of x conveniently demonstrates where subjects focus in relation to their normal responses to the single targets of a conflicting target pair (Figure 8.11). Plots of y versus x are shown for groups 1 and 2 in Figures 8.12 and 8.13 respectively. If the data cluster close to the vertical axis then the subject is focusing close to where they would normally focus for the attended target (Figure 8.11). Subject K exemplifies this type of response pattern (Figure 8.13e). If the data cluster close to the horizontal axis then the subject is focusing close to where they would normally focus for the conflicting target (Figure 8.11). Subject J spends some time focusing for the conflicting target (Figure 8.13d), and subjects C and E have outlier responses to the conflicting target (Figures 8.12c,e). When the data cluster at the origin the subject is focusing for both targets in trials where the attended and conflicting target are coincident (Figure 8.11).

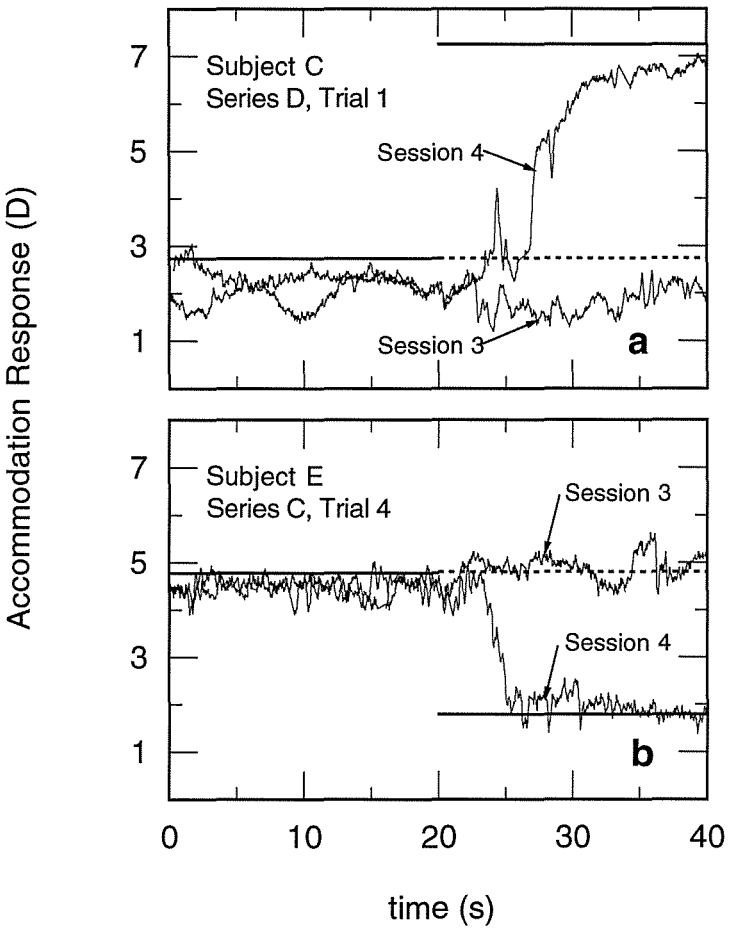


Figure 8.9. Accommodation responses of (**a**) subject C and (**b**) subject E demonstrating a failure to accommodate to the attended target in one session. Solid lines denote the stimulus levels of the adapting and attended targets in the adapting and viewing periods respectively. The dashed line denotes the stimulus level of the conflicting target.

If the data cluster in the upper right hand quadrant then the subject is focusing at a level higher than they normally would for either target (Figure 8.11). Subject C demonstrates this type of response (Figure 8.12c), and may have been focusing less accurately in Session 2 when the stimulus–response parameters were estimated. If the data cluster in the lower left hand quadrant then the subject is focusing at a level lower than they normally would for either target (Figure 8.11). Subject A demonstrates this type of response for some of the time (Figure 8.12a).

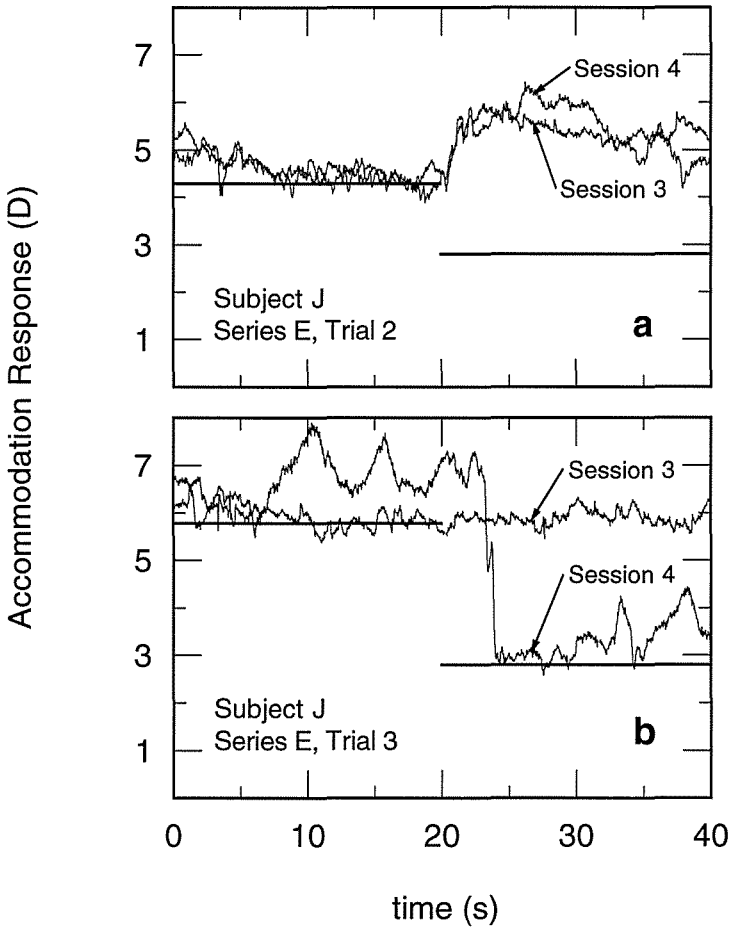


Figure 8.10. Accommodation responses of subject J in (**a**) trial 2 and (**b**) trial 3 of Series E demonstrating a failure to relax accommodation to the attended target in most trials. Solid lines denote the stimulus levels of the adapting and attended targets in the adapting and viewing periods respectively.

If the data cluster in the upper left hand quadrant or the lower right hand quadrant then the subject is focusing between where they normally would for either target (Figure 8.11). Some subjects spend a good proportion of the time focusing between targets (Figures 8.12b and 8.13b).

Subjects vary in the proportion of time they spend focusing at various positions in relation to the attended and conflicting targets (Figure 8.14). On average, subjects spend the most time focusing between the two conflicting targets (Table 8.5). They also spend more time focusing for the attended

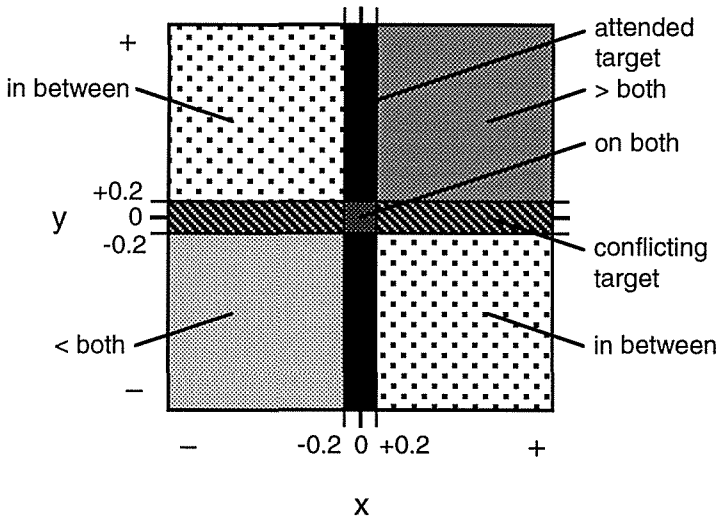


Figure 8.11. Various focus positions revealed in a plot of y as a function of x. The parameter x is the difference of the actual response from the predicted response to the attended target. The parameter y is the difference of the actual response from the predicted response to the conflicting target. If the actual response was within ±0.2 D of the predicted response for a target then the subject was considered to be focusing for that target.

target than the conflicting target, and this may be due to the definite instruction to attend to one particular target.

Comparison of the Three Models of Responses to Conflicting Targets

I compared the ability of the averaging model (ave), the gain suppression model (gs) and the intermediate resting position models (irp) to predict actual responses to conflicting targets. I used the absolute value of the model error (see equation 8.7) as a measure of model adequacy, and used multiple Wilcoxon Matched Pair Tests to compare the three models.[31]

The gain suppression model performs significantly better than the other models for 4 of the seven subjects (Table 8.6). The intermediate resting position model performs best for 1 of the seven subjects, and no model is superior for 2 of the subjects (Table 8.6). (Control models could not be

Figure 8.12. Plot of y as a function of x for Group 1 subjects. The parameter x is the difference of the actual response from the predicted response to the attended target. The parameter y is the difference of the actual response from the predicted response to the conflicting target. The data are collated for all trials of Series A, B, C and D in both sessions 3 and 4. The various symbols denote the amount of time spent at each focus position.

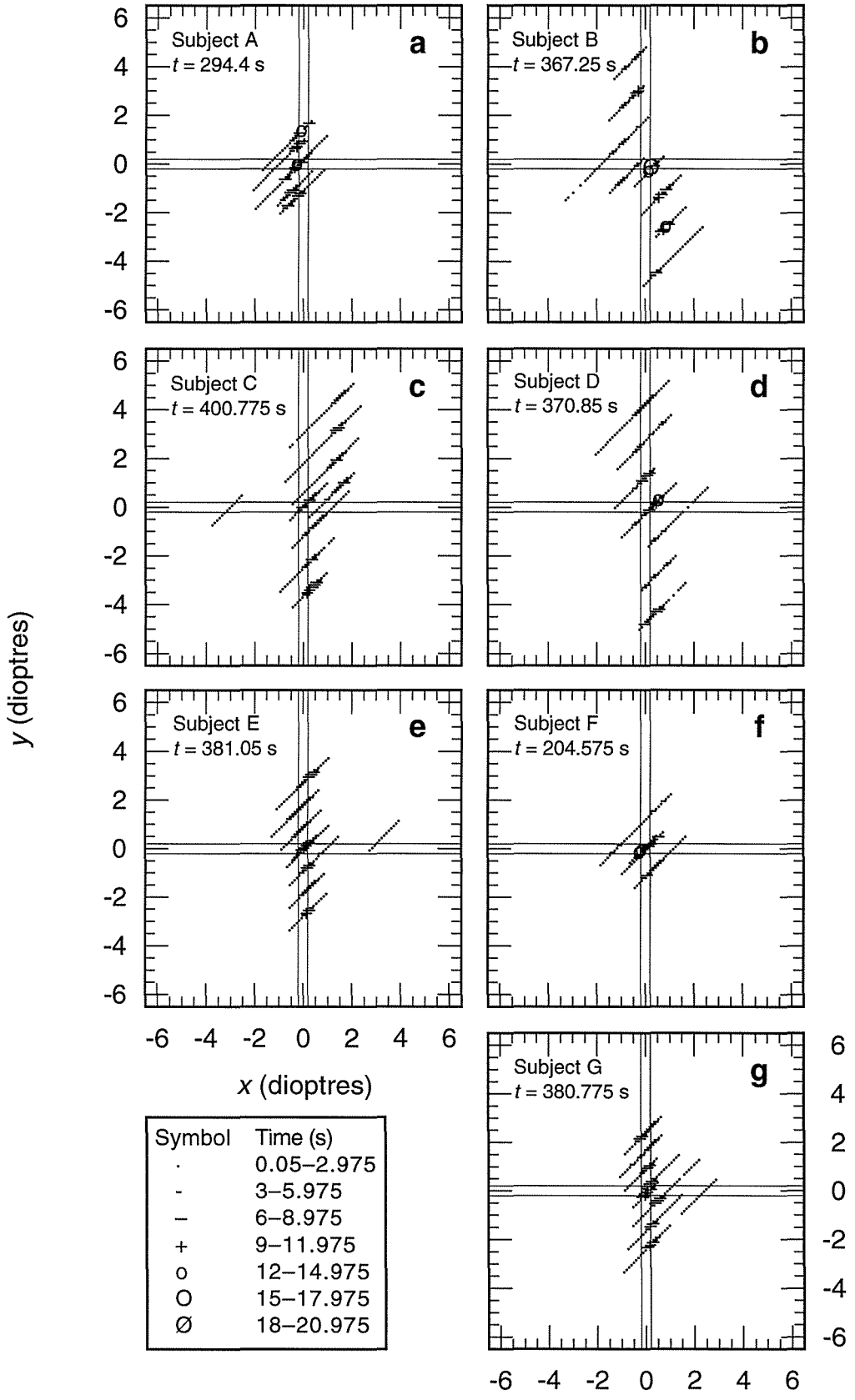
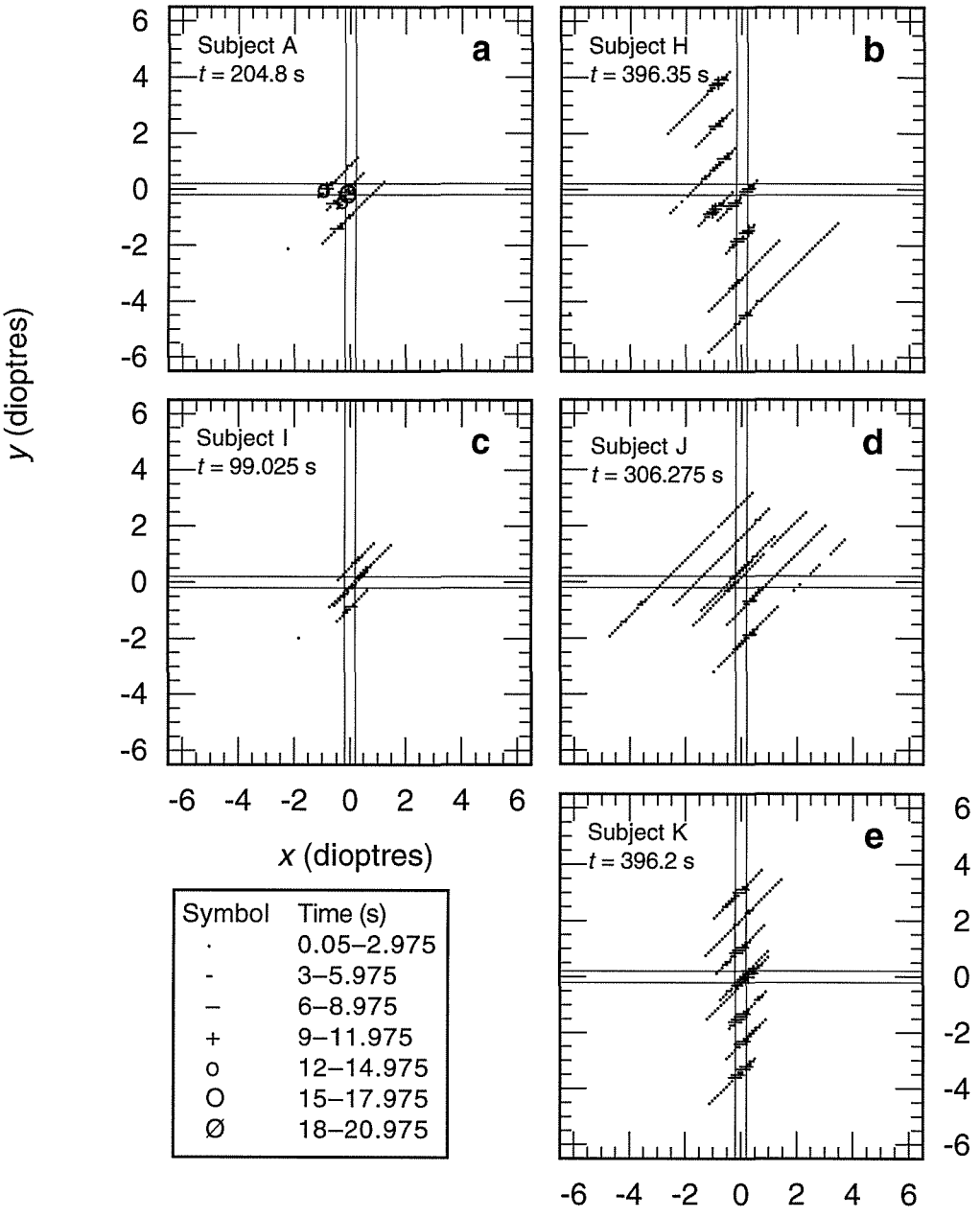

Subject A
t = 294.4 s
a
Subject B
t = 367.25 s
b
Subject C
t = 400.775 s
c
Subject D
t = 370.85 s
d
Subject E
t = 381.05 s
e
Subject F
t = 204.575 s
f
Subject G
t = 380.775 s
g
y (dioptres)
x (dioptres)
Symbol Time (s)
· 0.05–2.975
- 3–5.975
– 6–8.975
+ 9–11.975
o 12–14.975
O 15–17.975
Ø 18–20.975

Figure 8.13. Plot of y as a function of x for Group 2 subjects. The parameter x is the difference of the actual response from the predicted response to the attended target. The parameter y is the difference of the actual response from the predicted response to the conflicting target. The data are collated for all trials of Series A, B, C and D in both sessions 3 and 4. The various symbols denote the amount of time spent at each focus position.


Subject A
t = 204.8 s
a
Subject H
t = 396.35 s
b
Subject I
t = 99.025 s
c
Subject J
t = 306.275 s
d
Subject K
t = 396.2 s
e
y (dioptres)
x (dioptres)
6
4
2
0
-2
-4
-6
Symbol Time (s)
· 0.05–2.975
- 3–5.975
– 6–8.975
+ 9–11.975
o 12–14.975
O 15–17.975
Ø 18–20.975

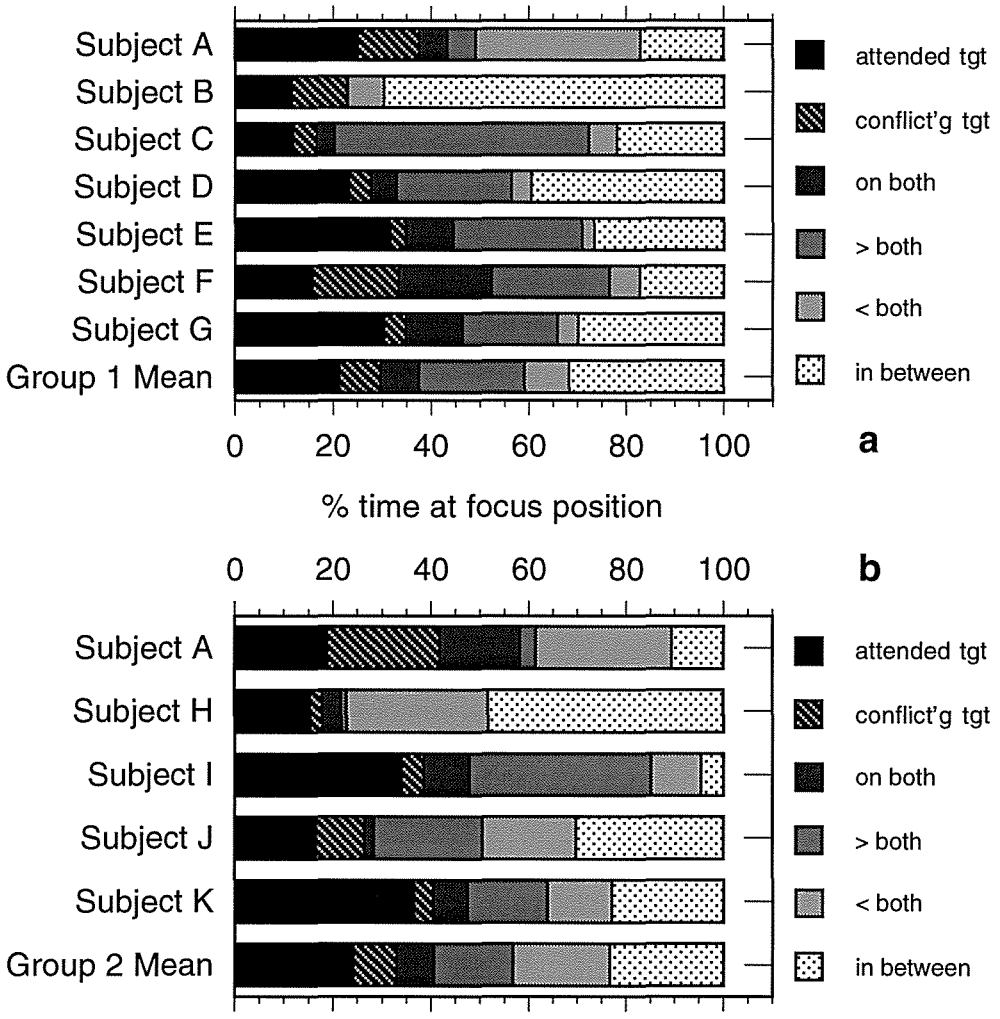


Figure 8.14. Proportion of time spent focused at various positions for subjects in (**a**) Group 1 and (**b**) Group 2. Positions are in relation to the *responses* to the single targets predicted from the respective stimulus–response functions. See Figure 8.11 for a graphical description of the various focus positions. If the actual response was within ±0.2 D of the predicted response for a target then the subject was considered to be focusing for that target.

applied to the data of five subjects because their accommodation stimulus–response function slopes were too close to +1.)

Plots of the model error as a function of target separation for representative subjects reveal how each model performed (Figures 8.15, 8.16). The gain suppression model best describes Subject C's responses to the conflicting targets (Figure 8.15b). For this subject the averaging model

Table 8.5. Probabilities that the proportions of time spent at the various focus positions are significantly different

	Probability (time @ Position A > time @ Positions B–G)					
A	*B in between*	*C attended tgt*	*D > both*	*E < both*	*F conflict'g tgt*	*G on both*
in between		0.48	0.18	**0.05**	**0.0096**	**0.0096**
attended tgt			0.24	0.08	**0.0076**	**0.0037**
> both				0.58	0.071	**0.023**
< both					0.16	0.21
conflict'g tgt						0.81
on both						

Tabled are the probabilities that the proportion of time spent at the position in the first column is greater than the proportion of time spent at focus positions in the other columns. The various focus positions are ordered: most time was spent focused between targets and the least time was spent focused on both targets. Multiple Wilcoxon matched pair tests were used on data pooled from Group 1 and Group 2. Entries in bold type are significant at the 5% level. No comparisons were significant at the Bonferroni corrected level of 0.33%.

performs poorly because it predicts that responses fall between two conflicting targets (Figure 8.15a). The intermediate resting position model performs quite well when the conflicting target is in front, but poorly when the conflicting target is behind the attended target (Figure 8.15c). This is because subject C's dark focus was lower than all levels of the attended and conflicting targets. When the conflicting target was close to the dark focus, the intermediate resting position model incorrectly predicted that the subject would focus for the conflicting target, when really she focused close to the attended target. An outlying response is marked in each plot with an arrow (Figures 8.15a,b,c). In this single trial the subject focused the target closest to her dark focus, even though she usually focused the attended target.

Subject J's accommodation responses to conflicting targets are best described by the intermediate resting position model (Figure 8.16c). Subject J

Table 8.6. Comparison of three models of the accommodation response to conflicting targets using multiple Wilcoxon matched pair tests

Subject	*Group**	*Model Rankings & Corresponding Mean Values of* |moderr|† *best performance.....worst performance*		
A	1	gs	irp	ave
		0.24	0.55	0.51
C	1	gs	irp	ave
		0.67	1.12	1.51
F	1	ave	gs ≈ irp	
		0.61	0.57 ≈ 0.57	
G	1	gs	ave	irp
		0.24	0.46	0.86
I	2	gs	ave	irp
		0.23	0.39	0.43
J	2	irp	gs	ave
		0.63	1.31	1.53
K	2	gs	ave	irp
		0.27	0.63	1.09

* Group 1 viewed bar targets and Group 2 viewed square gratings. † Wilcoxon tests were performed at $\alpha = 0.05$. Smaller values of $|moderr|$ indicate better performance by a model. See equation 8.7 for a description of the *moderr* parameter. 'ave' is the averaging model, 'gs' is the gain suppression model, and 'irp' is the intermediate resting position model. Note that the models are ranked by their mean ranking in the Wilcoxon test, and not by the their mean $|moderr|$ values. Two models not significantly different at the 5% level are single underlined. Three models not significantly different at the 5% level are double underlined.

tends to focus for the target closest to his dark focus despite the instruction to pay attention to the attended target.

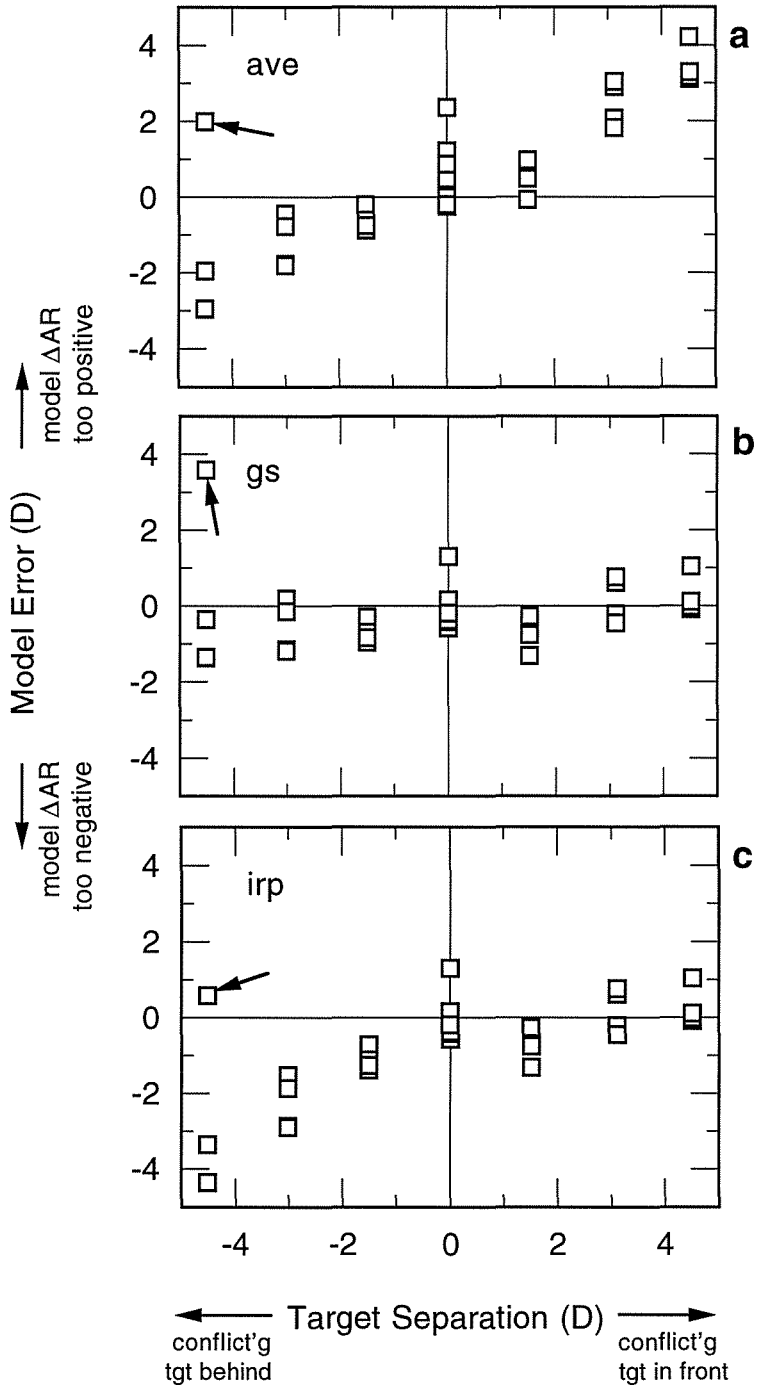


Figure 8.15. Model error as a function of separation of attended and conflicting targets for subject C. Model errors close to zero indicate that the model predicts actual responses well. Key: averaging model (ave); gain suppression model (gs); intermediate resting position model (irp). Arrows indicate an outlying point.

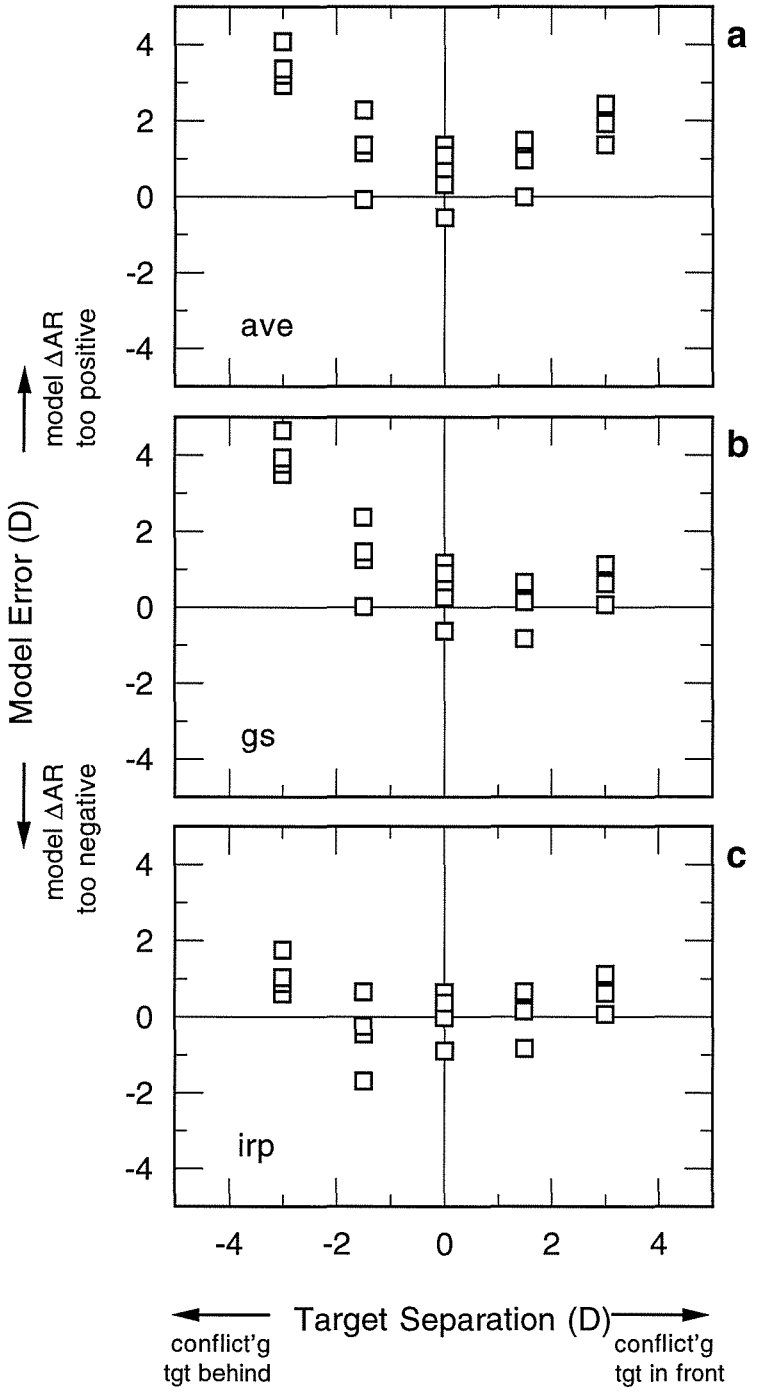


Figure 8.16. Model error as a function of separation of attended and conflicting targets for subject J. Other details are as for Figure 8.15.

8.4. Discussion

Upper Blur Thresholds

There are no definite upper blur thresholds of accommodation for any of the subjects in Group 1 or Group 2. It is remarkable that some subjects can focus for a 2 minute arc bar target that is initially defocused by over 5 D. There are two possible explanations for the lack of an upper blur threshold. One explanation is that subjects use low spatial frequency detail in the blurred target to initially guide the response and then use higher spatial frequency information as it becomes available. Another explanation is that subjects use voluntary accommodation to initially overcome large amounts of target defocus.

Subjects may use low spatial frequency detail in the blurred target to initially guide the accommodation response.[32-34] To investigate this possibility it would be necessary to know the target spatial frequency content and modulation, the modulation transfer function of the Badal optical system – eye combination, and the subject's retinal image modulation threshold. It would then be possible to determine which spatial frequencies of the bar and grating targets are supra-threshold for the subject at various amounts of target defocus.

Subjects may use voluntary accommodation to initially bring the blurred target clear. For example, Phillips noted that his subject made a step accommodation response to an anticipated but non-existent target, and that this 'voluntary' response was very similar to the subject's normal 'reflex' accommodation response.[18] Phillips called this type of response a *normal volitional accommodative response* to distinguish it from more active 'forced' responses. Subjects in this study may have used 'normal volitional accommodation' or they may have made true voluntary changes in their focus. However, because the dynamics of voluntary and 'reflex' accommodation responses are so similar,[35] it would be difficult to determine whether their responses are voluntary or 'reflex'. When initially presented with a high degree of target defocus, it is possible that the low spatial

frequency information present does not provide cues (e.g. chromatic aberration[23]) to the direction of defocus that are normally available at lower levels of defocus. The subject would be forced to make trial-and-error changes in focus until the response comes within the operating range of the reflex accommodation system.

The subjects in this study did not exhibit upper blur thresholds and so, at least for these subjects and the targets of this study, upper blur thresholds have no influence on the accommodation response to conflicting targets. It is possible though that upper blur thresholds exist for higher levels of defocus.[36]

Adapting Level Effects

There were no consistent and pronounced adapting level effects. Subjects' accommodation responses were generally not being 'captured' and held by the targets that happened to be closest to their adapting accommodation levels. Any adapting level effects are not statistically significant. Nevertheless, despite the absence of statistically significant effects, there are observations which suggest that adapting level effects are present. These effects probably do not reach statistical significance due to the small number of observations and the variability in the data.

One subject (K) appeared to be more susceptible to an adapting level effect for an intermediate separation (approximately 2.5 D) of two conflicting targets (Figures 8.7e,f). The subject's mean dark focus (0.1 D) was much lower than all target stimulus levels, ruling out the resting state of accommodation as a factor. A possible explanation is that the conflicting targets in this study provided the greatest stimulus to accommodation when blurred by about 2.5 D. However, Subject K was the only subject to clearly respond in this manner, and so the response pattern may be idiosyncratic.

One subject (J) on first analysis appeared to suffer from a negative adapting level effect; that is, he apparently focused more accurately for an attended target when first adapting at a very different accommodation level (Figure 8.8f). However these effects are actually due to his inability in many

trials to relax accommodation to the single targets in Series E (Figure 8.10). (Series E is used as a control when calculating the adapting level effect for the Series C versus A comparisons.) These responses are similar to the responses of some subjects of Charman and Heron for high spatial frequency sine gratings.[32] Heath also found that some subjects are 'reluctant' to relax accommodation when a target moves from a near to far dioptric distance.[37] Subject J's mean dark focus was 0.1 D so if the target was initially too blurred, his response should have decayed towards the dark focus. It is unlikely that a 20 second adapting period would bias the subject's dark focus upwards to about 5 D in addition to inducing tonic adaptation[27] sufficient to prevent the response from decaying by more than about 1 D in 20 seconds. Possibly the Badal optometer induced an 'instrument myopia' (see Chapter 3), but these effects were not observed in other trials. The subject did not show an upper blur threshold in Series F so an upper blur threshold is not responsible for the responses in Series E. The most likely explanation is that when presented with a step change in target vergence, subject J was uncertain where to focus, and used voluntary accommodation in an attempt to find the target. The high response level he adopted in two trials suggests that he thought the target was at a high stimulus level (Figure 8.10a). Subject J probably had active voluntary accommodation. During a practice session I noticed that subject J sometimes made large amplitude oscillations of accommodation to find the attended target. I repeated the instructions to the subject reminding him to view the targets naturally.

Two subjects usually did not exhibit an adapting level effect except for one trial when the conflicting target at the adapting level captured their focus (Figures 8.9a,b). These occasional gross failures suggest that the adapting level effect may be better described in a probabilistic way than in a deterministic way. So for example instead of citing an average value of the adapting level effect, it may be more appropriate to say that a person shows little adapting level effect 95% of the time, but shows a significant adapting level effect 5% of the time.

Because the adapting level effects were not statistically significant in this study I did not attempt to include them in later models. However the effects observed for some subjects in this study indicate that the adapting level probably does affect the response to conflicting targets.

If adapting level effects do exist then they have implications for drivers and pilots. For example, a pilot attempting to focus a distant airstrip through a rain covered windscreen may suffer a greater Mandelbaum effect if he or she had first been focusing to instrument panels in the cockpit.

Histogram Information on the Responses to Conflicting Targets

Previous studies have differed on the focus positions adopted by subjects when viewing conflicting targets.[4-6] In this study I did not compare dynamic accommodation responses to the stimulus levels of the two targets, but instead compared the dynamic responses to the single target responses predicted from stimulus–response function parameters. This method takes into account the normal inaccuracies of accommodation when viewing steady targets.

This study shows that for a wide variety of conflicting target configurations subjects do not adopt any single definite focus position (Figure 8.14 & Table 8.5). The actual proportion of time spent at various focus positions is arbitrary because of the arbitrary criterion used to define correct focus for a target (i.e. predicted response ±0.2 D). Nevertheless subjects on average spend the most time focused between targets. Whether or not this is due to a Mandelbaum effect is uncertain. It may be that the subjects normally have variable responses to a single target, and if a second target is present then it appears that they are focusing between the targets for some of the time. In this study there were not enough control conditions to rule out this possibility.

Subjects on average spent more time focusing for the attended target than the conflicting target (Table 8.5) and this is probably due to the definite instruction to attend to a particular target.

Models of the Accommodation Response to Conflicting Targets

COMPARISONS OF MODEL PERFORMANCE

The objective of this study was to predict accommodation responses to conflicting targets. In some ways I met this objective. Using the gain suppression model or the intermediate resting position model I was able to predict accommodation response changes on average to within 0.24 D to 0.67 D for five of the subjects (Table 8.6). For these subjects the models worked over a wide range of target stimulus levels and target separations, and for various prior adapting levels. However in other ways the models failed. None of the three control models in this study performed significantly better for two subjects (Table 8.6). In the case of subject F this was possibly due to the small range of stimulus separations. No model was superior for subject I probably because of the small number of data. Five subjects had stimulus–response function slopes too close to +1 to model without system instability. Of the seven subjects whose accommodation could be modelled, the modelled stimulus–response function intercepts were different by more than ±0.25 D from the actual intercepts for 4 subjects (Table 8.1). These model inadequacies are discussed later.

In summary, the ability to predict accommodation responses to conflicting targets is not as difficult as concluded by Rosenfield and Ciuffreda,[6] however some subjects' responses to conflicting (and single) targets still cannot be predicted. An important finding of this study is that there is *no one model* of accommodation for conflicting targets that works for all subjects. This study found two models that worked for some of the subjects, and it may be that future research will uncover other response patterns to conflicting targets.

THE AVERAGING MODEL

The averaging model generally performed poorly in predicting accommodation responses to conflicting targets (Table 8.5). It predicts that people focus between targets rather than on one of the two targets. The

likely reason for the averaging model's failure are the assumptions on which it is based. The accommodation controller gains were estimated for each target separately while the subject attended to a single target. These controller gains were then used to model the response to conflicting targets (Figure 8.5a). The problem here is that the averaging model assumes that the subject attends to both targets at the same time, when really they were probably only attending to one target at a time. The model also assumes that the subjects respond reflexively to single targets when in reality voluntary accommodation,[18] concentration or attention are also involved. The superiority of the gain suppression model over the averaging model reinforces this explanation.

THE GAIN SUPPRESSION MODEL

The gain suppression model was the most successful of the three models in this study (Table 8.6). Its simplicity is that it only requires blur information from the attended target — the conflicting target is completely ignored. The success of the gain suppression model for many subjects demonstrates that they were using voluntary effort to focus for an attended target.

An obvious inadequacy of the gain suppression model is that it predicts *no* Mandelbaum effect to conflicting targets, when in reality for some subjects there are small Mandelbaum effects (see for example Figure 8.12b,d). Perhaps the model could be altered so that the accommodation controller gain to the conflicting target can take on small values rather than zero (Figure 8.5b).

Despite the success and simplicity of the gain suppression model, is the model an accurate representation of the neural processes involved? The unanswered question which is basic to this problem relates to the normal accommodation response to single targets: Do we need to make voluntary effort to focus on an object, but then *relax* this voluntary effort if we do not wish to focus the object, or is it that reflex accommodation automatically brings the object into focus and we then have to use voluntary effort to *force* our focus away from the object? The gain suppression model makes no

distinction between voluntary and reflex components of accommodation: it simply models the responses of the subjects. The difficulty in this problem is separating the reflex and voluntary components of the accommodation response. However it is possible to speculate on the possible roles of reflex and voluntary components in the response.

True reflex accommodation is possibly limited to small errors of focus. This is because cues to the direction of accommodation such as chromatic aberration and fluctuations of accommodation would be weak for the low spatial frequency detail of a sufficiently blurred target.[38,39] However in normal viewing, people could use voluntary accommodation to initiate a response to large amounts of target defocus,[18] and thus place the response within the operating range of the reflex system. The reflex and voluntary systems combined would not exhibit an upper blur threshold, as for example was found in this study. When viewing conflicting targets, people may use voluntary accommodation to switch between the operating ranges of the reflex accommodation system for the respective targets. If two targets were closely spaced then people may use voluntary effort to force accommodation towards one of the two targets. These voluntary actions would correspond with subjects' reports that they need to make a constant effort to keep one target of a conflicting target pair in focus.[4] The gain suppression model would perform well in describing the responses of subjects that use voluntary accommodation to focus the attended target, even though the model oversimplifies the actual mechanisms.

Separate 'reflex' and voluntary components were not included in the gain suppresion model because I did not know their separate characteristics. This is a topic that needs research.

Voluntary accommodation may play another role in the response to conflicting targets. Subjects may use proprioceptive cues in conjunction with voluntary accommodation to map out the dioptric distances of targets in their field of view. Subjects in some studies have reported they can 'feel' their level of accommodation and can use this 'felt sensation' as an aid to focusing for a target.[40,41] These sensations can easily be demonstrated when

attempting to focus to the tip of a pencil placed close to the near point of accommodation. Take as a hypothetical example a subject viewing two targets in a Badal system; one target is at 2 D and the other at 4 D. There are no proximal cues available to the distance of the targets. The subject's accommodation response is initially at 1 D and the subject can feel that his accommodation level is low. If he then voluntarily accommodates to the 3 D level he will have noticed that the target at 2 D initially became clearer and then more blurred and that now his eye feels a little more strained. If he then accommodates voluntarily to 7 D he will have mapped out both targets in relation to an 'eyestrain' scale, and in relation to each other. The subject now knows that the target at 6 D is in front of the target at 2 D, and has thus obtained ordinal cues to the depth of the two targets. In other words, the subject has used voluntary accommodation to provide proximal cues.

THE INTERMEDIATE RESTING POSITION MODEL

One subject (J) tended to focus the target closest to his dark focus, and for this subject the intermediate resting position model was superior to the other models (Table 8.6, Figure 8.16). This was despite the definite instruction in this study to attend to one particular target. Other studies found that, when allowed to attend to either target of a conflicting target pair, many people focus on the target closest to their resting level of accommodation.[4,5] It may be that the 'default' focus position is the target closest to the dark focus of accommodation. However subjects with good voluntary accommodation may be able to escape this default position and focus on an attended target regardless of its position in relation to the dark focus.

CONTROL MODEL INADEQUACIES

There were two important inadequacies of the control models used in this study: firstly, an inability to model responses when the stimulus–response function slope was close to +1; and secondly, inaccuracies in modelling the steady stimulus–response function for single targets.

Inability to Model Some Stimulus–Response Functions

Three of the subjects in group 1 and two of the subjects in group 2 had stimulus response slopes too close to +1 to model without system instability. The problem is that high accommodation controller gain values are required to obtain high slope values, but the model becomes unstable for gain values greater than about twenty.[25] This problem is not an idiosyncrasy of my model but is common to all recent models of accommodation. Other studies have also found subjects with stimulus–response function slopes close to or greater than +1,[42] and dynamic responses to slowly moving sinusoidal targets with closed-loop gains greater than +1.[43]

There are a number of possible reasons why the control model is unable to model stimulus–response functions with high slope values. Hung *et al.* demonstrated that accommodation fluctuations (modelled as a sinusoidal input) can enhance the accommodation response for a given controller gain.[25] However, for one subject in this study I had to add fluctuations (actually a sinusoidal input at 1 Hz) of an unrealistically high amplitude to obtain even modest increases in stimulus–response function slope, and so abandoned this method. It is possible though that this method may work for some subjects. For a given accommodation controller gain, more accurate responses can be obtained if the depth of focus (DSP element) is smaller.[25] In this study I used the perceptual depth of focus, however accommodation can respond to stimulus changes smaller than the perceptual depth of focus.[44] Maybe the perceptual depth of focus I used in the model was greater than the true dead space of accommodation. Also, the depth of focus at the position of best subjective focus is greater than at points of focus to either side.[15,16] If accommodation lagged slightly behind the target then the depth of focus may have been smaller at this position than at the best focus position.

Even with depth of focus values of zero a negative feedback control model cannot model the responses of 4 subjects in this study who had stimulus–response slopes greater than or equal to +1. This is a property of the negative feedback system. To obtain amplification requires positive

feedback somewhere in the system. If there was a voluntary input to the system proportional to the accommodation response level then this would provide positive feedback. For example, subjects may use proprioceptive sensations to feel that they are focusing to a close distance and add voluntary effort in proportion to the felt sensation. These mechanisms are speculative but not unreasonable.

I cannot be confident that the stimulus–response slopes of some of the subjects in this study were definitely greater than +1 (Ninety five percent confidence intervals of the stimulus–response slopes were as follows: +1.08 – +1.24 for subject B viewing the horizontal target; +0.91 – +1.10 for subject D when viewing the vertical target; -0.28 – +2.36 for subject A in group 2 when viewing the vertical target; and +0.93 – +1.24 for subject H when viewing the vertical target). Also, it is possible that the high slope values are due to small inaccuracies in the individual Ophthalmetron calibration equations. Nevertheless, even if slopes were not greater than +1, they would still be high and difficult to model with current control system models.

The inability of current control models to model the accommodation responses of some normal subjects is an important inadequacy. This is not simply an unrealistic expectation that models should exactly match people's actual responses. Rather, the models are inadequate because they cannot model stimulus–response functions with slopes greater than +1, and because they approach instability when modelling stimulus–response functions with slopes close to +1.

Inaccurate Modelling of Stimulus–Response Functions

Even when it was possible to model the stimulus–response function, the model did not perform well for some subjects. The slopes of the stimulus–function could always be accurately modelled to within ±0.7%. However the stimulus–response function intercepts could not always be modelled accurately. For example, the model intercept lagged the actual intercept by between 0.85 D and 1.1 D for subject G. These lags can be reduced if a value of ABIAS higher than the dark focus is used in the model. Possibly the Ophthalmetron optometer induces an inward shift of the tonic state due to

its proximity to the eye,[20] whereas these proximal cues are absent when dark focus is measured with the Canon Autoref optometer in a large laboratory.

Some Factors in the Response to Conflicting Targets in This Study

All the subjects in this study had some previous experience in accommodation experiments. Possibly different results might have been obtained with naive subjects. For example if the naive subjects had poorly developed voluntary accommodation then proportionally more of the subjects may have responded in a way best described by the intermediate resting position model.

Two targets were used in this study. Subjects in group 1 viewed a bar target and subjects in group 2 viewed a square grating target. I thought it possible that subjects may 'cheat' with the bar targets by looking to one side of a conflicting bar target. This possibility cannot be ruled out, however it does not definitely explain the accurate responses of some subjects to the attended bar target. This is because three of the five subjects in Group 2 were able to focus well for the attended grating target (Figures 8.13b,c,e) even though the grating targets prevented them from cheating.

An interesting question which I did not investigate (due to the small number of trials) was whether subjects take longer to obtain a stable focus when viewing conflicting targets.

8.5. Summary

1. None of the subjects in this study exhibited an upper blur threshold. Some subjects were able to focus for targets even though they were initially grossly blurred. The upper blur threshold therefore cannot play a role in the response to conflicting targets, at least for the targets used in this study. However it may be that the lack of upper blur thresholds is due to the intrusion of voluntary accommodation, and that the upper blur thresholds of the reflex accommodation system do play a part in the response to conflicting targets.

2. The adapting level does not have a statistically significant effect on the response to conflicting targets. However when people adapt at an accommodation level close to a conflicting target, then the conflicting target can sometimes capture their focus. It may be better to describe the adapting level effect not in terms of an average effect, but rather as probabilities that an adapting level effect will or will not occur. Also some subjects did seem to be affected by the adapting accommodation level but the effects were not statistically significant. More research is needed.
3. Histogram analysis of dynamic accommodation responses demonstrates that people focus at many different positions in relation to two conflicting targets. On average people spend the most time focusing between where they normally would for the single targets of a conflicting target pair. In this study, subjects on average spent more time focused for an attended target than a conflicting target, and this is probably because of the definite instruction in this study to attend to one particular target.
4. The objective of this study was to predict accommodation responses to conflicting targets. This was possible for many subjects but not for all subjects. Therefore the ability to predict responses to conflicting targets is not as difficult as previously concluded;[6] however the models used in this study do not work for all subjects.
5. Many subjects' responses to conflicting targets could be modelled with a *gain suppression* control model. In this model the subject accommodates to a conflicting target pair as if they were focusing for the attended target by itself. The conflicting target is completely ignored. An inadequacy of the model is that it predicts no Mandelbaum effect when really there may be a small Mandelbaum effect. Even though the model works well, it probably oversimplifies the neural processes involved. The model may be realistic if it were to include separate reflex accommodation and voluntary accommodation components.

6. One subject's responses in this study were best modelled by the *intermediate resting position model*. He was focusing for the target which by itself gave a response closest to his dark focus. This model may represent the 'default' focus strategy, and with extra voluntary effort subjects may obtain responses best described by the *gain suppression model*.
7. The *averaging model* performed poorly in predicting responses to conflicting targets. This model predicts that the accommodation response is due to an 'averaging' of the blur signals from two targets weighted by the respective effectiveness of each target as an accommodation stimulus. The *averaging model* probably performs poorly because it assumes that people attend equally to both targets of a conflicting pair.
8. The control model in this study could not model some subject's steady responses to single targets. These subjects had stimulus–response functions with slopes close to or greater than +1. The failure of the control model may be because it uses a perceptual depth of focus which may be greater than the accommodation system dead space value. There may be a positive feedback path in the accommodation system.

References

1. Mandelbaum, J. An accommodation phenomenon. *A. M. A. Arch. Ophthalmol.* 1960, **63**, 923–926.
2. Fujii, K., K. Kondo and T. Kasai. *An analysis of the human eye accommodation system.* Osaka University, 1970. pp. 221–236. (Technical Report no. 925. vol. 20.)
3. Benel, R.A. *Visual Accommodation, the Mandelbaum Effect, and Apparent Size.* PhD thesis. Urbana-Champaign: University of Illinois, 1979.
4. Owens, D.A. The Mandelbaum effect: Evidence for an accommodative bias toward intermediate viewing distances. *J. Opt. Soc. Am.* 1979, **69**(5), 646–652.
5. Adams, C.W. and C.A. Johnson. Steady-state and dynamic response properties of the Mandelbaum effect. *Vision Res.* 1991, **31**(4), 751–760.
6. Rosenfield, M. and K.J. Ciuffreda. Accommodative responses to conflicting stimuli. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1991, **8**(2), 422–427.
7. Collins, M., B. Davis and D. Atchison. VDT screen reflections and accommodation response. *Ophthalmic Physiol. Opt.* 1994, **14**, 193–198.

8. Chong, J. and T.J. Triggs. Visual accommodation and target detection in the vicinity of a window post. *Hum. Factors.* 1989, **31**(1), 63–75.
9. Hung, G.K. and J.L. Semmlow. Static behavior of accommodation and vergence: computer simulation of an interactive dual-feedback system. *IEEE Trans. Bio.-Med. Eng.* 1980, **BME-27**(8), 439–447.
10. Schor, C.M., J. Alexander, L. Cormack and S. Stevenson. Negative feedback control model of proximal convergence and accommodation. *Ophthalmic Physiol. Opt.* 1992, **12**, 307–318.
11. Ciuffreda, K.J., N.A. McBrien and S.K. Fisher. Accommodation with and without foveal contribution [Abstract]. *Optom. Vision Sci., Suppl.* 1989, **66**(10), 108.
12. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction.* Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
13. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.
14. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin.* 1972, **77**(1), 54–64.
15. Campbell, F.W. and G. Westheimer. Sensitivity of the eye to differences in focus [Abstract]. *Journal of Physiology. Supplementum.* 1958, **143**, 18P.
16. Walsh, G. and W.N. Charman. Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Res.* 1988, **28**(11), 1207–1221.
17. Campbell, F.W. The depth of field of the human eye. *Opt. Acta (Paris).* 1957, **4**(4), 157–164.
18. Phillips, S.R. *Ocular Neurological Control Systems: Accommodation and the Near Response Triad.* PhD Thesis. Berkeley: University of California, 1974. pp. 289–339; 340–360.
19. Schor, C.M., J.C. Kotulak and T. Tsuetaki. Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. *Invest. Ophthalmol. Visual Sci.* 1986, **27**(5), 820–827.
20. Jaschinski-Kruza, W. On proximal effects in objective and subjective testing of dark accommodation. *Ophthalmic Physiol. Opt.* 1991, **11**, 328–334.
21. Rosenfield, M. and K.J. Ciuffreda. Effect of surround propinquity on the open-loop accommodative response. *Invest. Ophthalmol. Visual Sci.* 1991, **32**, 1, 142–147.
22. Rosenfield, M., K.J. Ciuffreda and G.K. Hung. The linearity of proximally induced accommodation and vergence. *Invest. Ophthalmol. Visual Sci.* 1991, **32**(11), 2985–2991.
23. Kruger, P.B., S. Mathews, K.R. Aggarwala and N. Sanchez. Chromatic aberration and ocular focus: Fincham revisited. *Vision Res.* 1993, **33**(10), 1397–1411.
24. Shirachi, D., J. Liu, M. Lee, J. Jang, J. Wong and L.W. Stark. Accommodation dynamics. 1. Range nonlinearity. *Am. J. Optom. Physiol. Opt.* 1978, **55**(9), 631–641.
25. Hung, G.K., J.L. Semmlow and K.J. Ciuffreda. Accommodative oscillation can enhance average accommodative response: a simulation study. *IEEE Trans. Syst., Man, Cybern.* 1982, **SMC-12**(4), 594–598.
26. Krishnan, V.V. and L.W. Stark. Integral control in accommodation. *Comput. Programs Biomed.* 1975, **4**, 237–245.
27. Hung, G.K. Adaptation model of accommodation and vergence. *Ophthalmic Physiol. Opt.* 1992, **12**, 319–326.
28. Bannon, R.E. The use of cycloplegics in refraction. *Am. J. Optom. Arch. Am. Acad. Optom.* 1947, **24**(11), 513–568.

29. O'Neill, W.D. An interacting control systems analysis of the human lens accommodative controller. *Automatica.* 1969, **5**, 645–654.
30. Sokal, R.R. and F.J. Rohlf. *Biometry.* 2nd ed. San Francisco: W. H. Freeman, 1981. pp. 594–601.
31. Marascuilo, L.A. and M. McSweeney. *Nonparametric and Distribution-Free Methods for the Social Sciences.* Monterey, CA: Brooks/Cole, 1977. pp. 330–344.
32. Charman, W.N. and G. Heron. Spatial frequency and the dynamics of the accommodation response. *Opt. Acta (Lond.).* 1979, **26**(2), 217–228.
33. Tucker, J., W.N. Charman and P.A. Ward. Modulation dependence of the accommodation response to sinusoidal gratings. *Vision Res.* 1986, **26**(10), 1693–1707.
34. Tucker, J. and W.N. Charman. Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 137–142.
35. Ciuffreda, K.J. and P.B. Kruger. Dynamics of human voluntary accommodation. *Am. J. Optom. Physiol. Opt.* 1988, **65**(5), 365–370.
36. Provine, R.R. and J.M. Enoch. On voluntary ocular accommodation. *Percept. Psychophys.* 1975, **17**(2), 209–212.
37. Heath, G.G. The influence of visual acuity on accommodative responses of the eye. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956, **33**(10), 513–524.
38. Charman, W.N. and J. Tucker. Accommodation as a function of object form. *Am. J. Optom. Physiol. Opt.* 1978, **55**(2), 84–92.
39. Stone, D., S. Mathews and P.B. Kruger. Accommodation and chromatic aberration: effect of spatial frequency. *Ophthalmic Physiol. Opt.* 1993, **13**(3), 244–252.
40. Bour, L.J. The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Res.* 1981, **21**, 1287–1296.
41. Ciuffreda, K.J. and S.C. Hokoda. Effect of instruction and higher level control on the accommodative response spatial frequency profile. *Ophthalmic Physiol. Opt.* 1985, **5**(2), 221–223.
42. Ciuffreda, K.J., S.C. Hokoda, G.K. Hung and J.L. Semmlow. Accommodative stimulus/response function in human amblyopia. *Doc. Ophthalmol.* 1984, **56**(4), 303–326.
43. Krishnan, V.V., S. Phillips and L.W. Stark. Frequency analysis of accommodation, accommodative vergence and disparity vergence. *Vision Res.* 1973, **13**, 1545–1554.
44. Kotulak, J.C. and C.M. Schor. The accommodative response to subthreshold blur and perceptual fading during the Troxler phenomenon. *Perception.* 1986, **15**, 7–15.

Chapter 9

Conclusions and Further Research

I have studied a number of factors contributing to the accommodation responses for single and multiple stimuli. I first investigated the effects of subject instructions, methods of target presentation, and pupil size on the characteristics of accommodation responses to single targets. I then modelled the accommodation response to peripheral stimuli, and investigated whether the accommodation response to an extended target can be predicted from the responses to its constituent parts. Finally, I investigated the effects of voluntary accommodation, target contrast, upper blur threshold, and adapting level effects on the accommodation responses to conflicting targets, and used control system models to predict these responses.

9.1. Subject Instructions

Previous research suggested that instructions can affect accommodation, but the effects of instructions were not systematically investigated. I found that instructions can influence subjects to make voluntary changes in their accommodation or conscious changes in their normal attention to a target (Chapter 3). Researchers must therefore choose subject instructions carefully if they wish to obtain accommodation responses representative of their subjects' normal responses in a particular situation.

Responses to steady targets with an instruction to 'view the target naturally' are not significantly different from responses with the instruction to 'focus carefully'. Furthermore, the responses with these two instructions are only slightly different from the responses obtained with a minimal instruction to stabilise gaze ('pick a word in the middle of the block of text and look at it'). Thus, responses with instructions to 'view the target naturally' or to 'focus carefully' are likely to be close to people's normal accommodation responses.

In contrast, accommodation responses vary widely between individuals when they are instructed to 'make no special effort' when viewing the target. Some subjects adopt a fairly stable low accommodation level with this instruction, others show fluctuating responses, and still others focus fairly accurately for the target. The instruction to 'make no special effort' leads some people to use voluntary accommodation to relax their focus, while others try to suspend their normal attention to a target.

The marked effects of subject instructions found in this study indicate that voluntary accommodation and cognitive factors can have significant influences on the accommodation stimulus–response function.

This study investigated the steady state response of accommodation, and it is likely that instructions also lead to differences in the various dynamic characteristics of accommodation.[1,2] Also, the interrelationships between subject instructions and target form are potentially of importance to oculomotor research where a wide variety of targets is used.

9.2. Methods of Target Presentation

Badal optical systems are widely used in accommodation research but it has not previously been shown that responses with these systems are equivalent to responses for targets presented in real space. I found that most people can accommodate adequately for steady targets presented in Badal optical systems even though these optical systems remove many of the proximal stimuli to accommodation normally found in real scenes (Chapter 3). When viewing targets in Badal systems, people may use the low spatial frequency detail to initially guide the response to an out of focus target.[3,4] They may also use voluntary accommodation to hunt for the focus position of the target. Some people have difficulties focusing for targets in Badal systems, and this could be due to a reliance on proximal stimuli to accommodation, to poor voluntary accommodation, or to a susceptibility for erroneous proximal cues provided by the Badal system.[5]

9.3. Pupil Size

Previous studies of the effects of pupil size on the high frequency fluctuations of accommodation are conflicting.[6,7] I found that pupil size (1–6 mm diameter) does not significantly influence the high frequency (0.7–2.53 Hz) fluctuations of accommodation (Chapter 4). Previous studies conflicted over whether a high frequency peak in the accommodation power spectrum changes with pupil size.[6,7] I found one subject (of four) who showed a decrease in this high frequency peak with smaller pupils, and another subject who showed exactly the opposite. Furthermore, a comparison of mean and median power spectra for one subject suggests that an occasional outlier can bias the mean power spectrum curve. Thus it may be that the accommodation system occasionally becomes unstable (for whatever reason) leading to an increase in the 2 Hz fluctuations of accommodation.[8] This occasional instability makes it appear as if pupil size affects the 2 Hz fluctuations of accommodation.

Small pupils lead to an increase in the magnitude of the low frequency fluctuations of accommodation independent of both mean accommodation level and retinal illuminance. It has been previously hypothesised that the low frequency fluctuations of accommodation are used to aid the steady state accommodation response.[9] However an alternative interpretation is that the increased depth of focus with small pupils allows voluntary, proximal and cognitive influences to alter the accommodation response over a larger range without subjective blur of the target. All studies to date (including the present study) have not sampled accommodation for a sufficiently long enough time period to determine the characteristics of the low frequency fluctuations with various pupil sizes.

This study and others have used fixed artificial pupils and the effect of pupil size on fluctuations of accommodation needs to be investigated for levels of pupil size, retinal illuminance and mean accommodation response level representative of real situations.

9.4. Peripheral Stimuli to Accommodation

Previous studies of peripheral stimuli to accommodation have used steady or predictable dynamic targets, and with these targets, subjects may use voluntary accommodation to obtain a better accommodation response. These studies could not determine whether 'reflex' accommodation occurs to the blur of peripheral targets. The quickly moving sinusoidal motion of some of the targets in my study (while still predictable) would have prevented voluntary trial-and-error hunting of accommodation. In my study, one subject may have been using voluntary accommodation to track slowly moving peripheral targets, but the other subject probably was not using voluntary accommodation (Chapter 5). Further research is needed to determine what roles voluntary and reflex accommodation play in the response to peripheral target detail. The roles of voluntary and reflex accommodation in peripheral accommodation could be investigated by comparing responses to unpredictable and predictable target motion. This

could be achieved using Gaussian noise as an unpredictable target stimulus and a square wave temporal stimulus as a predictable target stimulus.

Current quantitative models of accommodation only consider single, centrally viewed targets, but in the real world there are usually objects in both the central and peripheral fields of view. I developed a dynamic control model of the accommodation response to peripheral stimuli but it incorrectly predicts a more accurate dynamic accommodation response for larger targets. Contrary to my control model and to previous studies, I found that the dynamic accommodation response does not become more accurate for targets increasing in size from 0.5° to 2.9° radius.[10,11] This finding contradicts the view that there is pooling of central and paracentral blur information to the higher accommodation control centres.

The failure of the model may be due to its assumption that subjects attend equally for both central and peripheral target detail, when in reality they may selectively attend to the central detail. The effect of attention on the accommodation response to peripheral targets needs to be investigated. To address this factor of *attention*, it would be necessary to measure accommodation to peripheral targets both with and without attention to the targets. This could be done by optically providing a central fixation target viewed through a small pupil (0.5 mm) so that it provided no stimulus to accommodation.[12] The peripheral target would be viewed through the normal pupil. Accommodation could be recorded while the subject either attended to the central target or to the peripheral target. This experiment would show whether attention affects accommodation to peripheral targets.

A topic which needs to be investigated is whether accommodation to peripheral targets can be improved if the target detail is scaled to be as equally visible as central target detail. Both visual acuity and contrast sensitivity are equivalent in central and peripheral vision if the targets are scaled to give equivalent cortical representations.[13-15] This raises the question of whether accommodation may also be equivalent for M-scaled targets in peripheral vision. Perhaps the poor accommodation found for peripheral targets is simply due to their decreasing cortical representation.

The control model in this study did not perform well at predicting the accommodation responses to extended targets. However if a model could be developed that works well for equi-distant targets, then a good test of this model would be to see how it performs with conflicting central and peripheral targets. Such a model would be useful in predicting accommodation responses for real scenes where objects occur at many different distances and at many different locations in the visual field. For example, when viewing a real three dimensional object, the detail on the surfaces of the object can be at different distances from the eye, and at different eccentricities from the line of sight.

9.5. Factors in the Accommodation Responses to Conflicting Targets

I hypothesised that a number of factors may help to explain the wide variability in accommodation responses to conflicting targets previously reported in other studies. None of these factors have previously been investigated. One factor which I controlled for but did not investigate was the *subject instructions*. I gave subjects an instruction that required them to attend to only one target. The variable responses to conflicting targets found in some previous studies may have been due to the instructions which allowed subjects to attend to either of two conflicting targets at will.

While I used a definite instruction in this study, other instructions may be more appropriate for applied research. In this study subjects had to attend carefully to a target for about 40 seconds. But would a person be able to continue at this task for longer periods of time? Would they normally attend so carefully to objects of interest in every-day situations? For example, a VDT operator viewing screen text with an overlying screen reflection would probably not pay constant attention to the screen text. In this situation it may be more natural to dispense with focusing instructions and simply give an instruction related to the VDT task.

Voluntary Accommodation

Previous studies contain suggestions that subjects may use voluntary accommodation when viewing conflicting targets. I found that many people do not use memorised voluntary accommodation to overcome the unwanted accommodation response to a conflicting target: that is, they do not focus for the desired target by locking on to the memorised focus level of the desired target (Chapter 6). Many subjects are able to overcome the Mandelbaum effect (i.e. the unwanted accommodation response to a conflicting target), even though they have poor memorised voluntary accommodation.

There is evidence that subjects do use voluntary accommodation (other than memorised voluntary accommodation) when viewing conflicting targets. In another study, the accommodation responses of several subjects to conflicting targets were best predicted by a 'gain suppression' control model (Chapter 8). This model assumes that the subjects completely ignore a conflicting target and focus for an attended target. The success of this model over a wide range of target separations and stimulus levels suggests that these subjects use voluntary accommodation to ignore the conflicting target.

One way to positively demonstrate the presence of voluntary accommodation in the responses to conflicting targets would be to measure the response to a distant target by itself, to a near target by itself, and to the distant–near target combination with the subject instructed either to focus the distant target or the near target. The difference in responses to the combined target with the two instructions would be due to conscious control of accommodation. This experiment would demonstrate if voluntary accommodation existed but it would not tell which form of voluntary accommodation was being used; for example, normal attention and concentration, or an active hunting for best focus.

Proximal Accommodation

An incidental finding is that the proximal cues provided by conflicting and attended targets may play a role in the Mandelbaum effect (Chapter 6). I found that when subjects viewed a distant target in real space through an

intervening mesh, the contrast of the distant target could be reduced to 0% and the mesh still could not induce a significant Mandelbaum effect (Chapters 6 & 7). If an attended target provides sufficient proximal cues to accommodation then these may be used to overcome the Mandelbaum effect to a conflicting target, even though the conflicting target provides strong blur stimuli to accommodation.

Conflicting targets may also interfere with size and distance perception, as noted by some subjects in one of my studies (Chapter 6). Conflicting targets may affect size and distance perception by causing a perceptual flattening of a real scene,[16,17] or by providing erroneous proximal cues via Gestalt figure-ground relationships (Chapter 6).[18] For example, if a subject focuses for a distant target, then a blurred mesh at a nearer distance may appear as a 'ground' on which the distant target (the 'figure') rests. Accommodation micropsia and macropsia associated with the Mandelbaum effect may also affect the perceived sizes and distances of objects in the field of view.[19]

The effects of proximal stimuli on the accommodation response to conflicting targets could be further investigated by determining the accommodation responses to blur stimuli alone (viewing in a Badal system), proximal stimuli alone (viewing a real scene through a 0.5 mm pupil), or with both blur and proximal stimuli present (natural viewing of a real scene).

Upper Blur Thresholds

The upper blur threshold is the maximum amount of target blur that can elicit an accommodation response. I hypothesised that if a conflicting target is beyond the upper blur threshold then it will not provide a conflicting stimulus to accommodation. I found that the measured upper blur threshold is unlikely to play a significant role in the responses to conflicting targets. In one study, none of the subjects showed an upper blur threshold for a 2 minute arc bar target, in some cases even when the target was initially blurred by over 5 D (Chapter 8). However, it is possible that the upper blur

threshold measured in this study is contaminated by voluntary accommodation which would have acted to overcome large amounts of blur.

Further research is needed to determine the upper blur threshold of the 'reflex' accommodation system, separate of voluntary accommodation. This could be done by analysing a large number of responses to random and unpredictable target steps. It may be found that accommodation initially responds correctly to small target steps due to the availability of cues to 'reflex' accommodation, but initially responds randomly to larger target steps (representing trial-and-error voluntary accommodation changes).

Adapting Level Effects

I hypothesised that the prior adapting level of accommodation may bias the response to conflicting targets. I found that the adapting level of accommodation just prior to viewing a set of conflicting targets does not have any obvious, consistent and statistically significant effect on the responses to conflicting targets (Chapter 8). However when people adapt at the level of a conflicting target, then this target can sometimes capture their focus and prevent them from accommodating to another attended target. As these effects are only noted occasionally, it may be better to describe them not in terms of an average effect, but in terms of the probability of their likely occurrence. There possibly are small adapting level effects but they did not reach statistical significance in my study.

9.6. Predicting Responses to Conflicting Targets

Present models of accommodation only consider the accommodation responses to single targets. I developed three control models of the steady accommodation response to conflicting targets, and then compared these models to actual responses to see which (if any) of the models performed best at predicting actual responses to conflicting targets (Chapter 8). This study clearly shows that no single model can describe every subject's

accommodation response to conflicting targets: subjects respond in different ways best described by different models.

The *averaging model* predicts that the accommodation response for two conflicting targets is an 'average' of the blur signals from the two targets weighted by the effectiveness of each target as an accommodation stimulus. The averaging model performs poorly in predicting subjects accommodation responses, probably because it assumes that people attend equally to both conflicting targets. Some people focus to the target that gives a response closest to their tonic accommodation level, as predicted by the *intermediate resting position model*. The *gain suppression model* performs quite well in predicting the responses of some subjects to conflicting targets. This model assumes that the accommodation system completely suppresses any response to the conflicting target. Even though the gain suppression model works quite well, it probably oversimplifies the neural processes involved. It is possible that the reflex response to a conflicting target is still active over a small dioptric range, but that subjects use voluntary accommodation to bias accommodation towards an attended target so that, effectively, it is as if the conflicting target has no effect on accommodation.

Not all subjects' responses to conflicting target can be adequately modelled, however the results so far indicate that control system models can be extended to the case of multiple stimuli, and that these models do work for many subjects. Thus the possibility of modelling accommodation responses to conflicting targets is not so bleak as has been previously concluded.[20]

A hurdle that control models of the accommodation response to conflicting targets will have to face is that in many real situations the targets occur at infinite distance or low dioptric levels. These targets fall within the non-linear region of the accommodation response profile (section 1.2.1.),[11] a zone which no-one has attempted to model, even for single stimuli.

Implications of Research on Multiple Stimuli for Models of Single Stimuli to Accommodation

I found some subjects whose steady accommodation stimulus–response function slopes were too close to +1 to model using a negative feedback control model (Chapter 8). This is an inadequacy of present control models, and suggests that there may be positive feedback somewhere in the accommodation feedback system. A possible source of positive feedback is voluntary accommodation.

Two control models of the accommodation response to conflicting stimuli developed in Chapter 8 (the averaging model and the gain suppression model) demonstrate the importance of attention and/or voluntary accommodation in the response to single and conflicting targets. Blur stimuli, attention and voluntary accommodation are all likely to act in unison when viewing a single target. In control models for single targets there is no need to model reflex and voluntary accommodation separately because the two are so similar in their characteristics and because they work in unison. However with conflicting targets there are conflicting blur cues provided by the two targets, and attention and voluntary accommodation may be directed to either of the targets. Future models of the accommodation response to conflicting targets will need to consider the separate effects of both reflex and voluntary accommodation.

References

1. van der Wildt, G.J., M.A. Bouman and J. van de Kraats. The effect of anticipation on the transfer function of the human lens system. *Opt. Acta (Lond.)*. 1974, **21**(11), 843–860.
2. Kruger, P.B. Infrared recording retinoscope for monitoring accommodation. *Am. J. Optom. Physiol. Opt*. 1979, **56**(2), 116–123.
3. Charman, W.N. and G. Heron. Spatial frequency and the dynamics of the accommodation response. *Opt. Acta (Lond.)*. 1979, **26**(2), 217–228.
4. Tucker, J. and W.N. Charman. Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. *Ophthalmic Physiol. Opt*. 1987, **7**(2), 137–142.
5. Schor, C.M., J. Alexander, L. Cormack and S. Stevenson. Negative feedback control model of proximal convergence and accommodation. *Ophthalmic Physiol. Opt*. 1992, **12**, 307–318.
6. Campbell, F.W., J.G. Robson and G. Westheimer. Fluctuations of accommodation under steady viewing conditions. *J. Physiol*. 1959, **145**, 579–594.

7. Gray, L.S., B. Winn and B. Gilmartin. Accommodative microfluctuations and pupil diameter. *Vision Res.* 1993, **33**(15), 2083–2090.
8. Stark, L.W., Y. Takahashi and G. Zames. Nonlinear servoanalysis of human lens accommodation. *IEEE Trans. Syst. Sci. Cybern.* 1965, **SSC-1**(1), 75–83.
9. Charman, W.N. and G. Heron. Fluctuations in accommodation: a review. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 153–164.
10. Ciuffreda, K.J., N.A. McBrien and S.K. Fisher. Accommodation with and without foveal contribution [Abstract]. *Optom. Vision Sci., Suppl.* 1989, **66**(10), 108.
11. Ciuffreda, K.J. Accommodation and its anomalies. *In:* J. Cronly-Dillon ed. *Vision and Visual Dysfunction.* Houndmills, Hampshire: The Macmillan Press, 1991. W.N. Charman ed. vol. 1, Visual Optics and Instrumentation. pp. 231–279.
12. Ward, P.A. and W.N. Charman. On the use of small artificial pupils to open-loop the accommodation system. *Ophthalmic Physiol. Opt.* 1987, **7**(2), 191–193.
13. Virsu, V. and J. Rovamo. Visual resolution, contrast sensitivity, and the cortical magnification factor. *Exp. Brain Res.* 1979, **37**, 475–494.
14. Rovamo, J. Cortical magnification factor and contrast sensitivity to luminance-modulated chromatic gratings. *Acta Physiol. Scand.* 1983, **119**, 365–371.
15. Pointer, J.S. Visual representation at the cerebral cortex: qualitative and quantitative aspects. *Ophthalmic Physiol. Opt.* 1986, **6**(2), 171–175.
16. Gogel, W.C. Equidistance tendency and its consequences. *Psychological Bulletin.* 1965, **64**(3), 153–163.
17. Eby, D.W. and M.L. Braunstein. The perceptual flattening of 3D scenes enclosed by a frame [Abstract]. *Invest. Ophthalmol. Visual Sci., Suppl.* 1993, **34**(4), 1184.
18. Bruce, V. and P.R. Green. *Visual Perception: Physiology, Psychology and Ecology.* 2nd ed. Hove, East Sussex, U.K.: Lawrence Erlbaum Associates, 1990. pp. 105–139.
19. Holst, E., von. *The Behavioural Physiology of Animals and Man* [Zur Verhaltensphysiologie bei Tieren und Menschen: Gesammelte Abhandlungen]. translated by R. Martin. London: Methuen, 1973. vol. 1. pp. 185–187.
20. Rosenfield, M. and K.J. Ciuffreda. Accommodative responses to conflicting stimuli. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1991, **8**(2), 422–427.

Appendix A

Canon Autoref R-1 Optometer

A.1. Description of the Canon Autoref R-1

The Canon Autoref R-1 is a clinical objective infra-red optometer introduced by Canon Incorporated (Japan) in 1981, but now discontinued. The Autoref allows the subject a binocular, open field of view through an infra-red reflecting beam splitter. The field of view is approximately 50° wide by 22° deep, although parts of the instrument intrude inferiorly within 7° of fixation. An examiner views the subject's eye in a video monitor and aligns the Autoref using a joystick control. (See McBrien and Millodot for a photograph of the Autoref.[1]) The Autoref samples the refractive error along three meridians separated by 60°, and from these values determines the sphero-cylindrical refractive error. A single reading takes 0.2 second. Matsumura *et al.*[2] and McBrien and Millodot[1] have described the design of the Autoref optometer.

Autoref readings show good repeatability both within and between sessions.[1] The Autoref gives valid readings of refractive sphere component, but cylindrical components tend to be too high, and axes are incorrect in eyes with small degrees of astigmatism.[1,3] Autoref readings are unaffected by pupils ≥ 3 mm,[4] but show spurious cylindrical components for pupils smaller than 3 mm.

Autoref Units used in this Thesis

I used two Autorefs in this thesis, and both reside in the Centre for Eye Research. The first Autoref is held in Michael Collins' laboratory, and the second Autoref in David Atchison's laboratory. The first Autoref has been modified to measure accommodation continuously,[5] but can still operate in its standard 'static shot' mode. When I was using the first Autoref it was set to give refraction readings referenced to a 12 mm vertex distance. In October 1993, the second Autoref was modified to provide refraction readings referenced to the corneal vertex. Before this time readings were referenced to a 12 mm vertex distance.

VERTEX DISTANCE SETTINGS ON THE AUTOREF

The Autoref can be set to provide refraction readings referenced to the corneal vertex or to a point 12 mm from the corneal vertex. This is done by setting toggle 4 on switch 10 of the signal conditioning board (Figure A.1). Toggle 4 is set to the ON position for a 12 mm vertex distance, or to the OFF position for a 0 mm vertex distance.

MODIFICATION TO EYE-FRONT ILLUMINATION

In normal operation, light passes from two eye-front illuminating lamps through two infra-red transmitting filters to illuminate the eye.[1] These filters pass some light in the red region of the visible spectrum, and are visible to the subject in a dark room as two small red lights, one located nasally and one temporally at eccentricities of about 20°. Due to their retinal location and spatial content, they are unlikely to provide a blur stimulus to

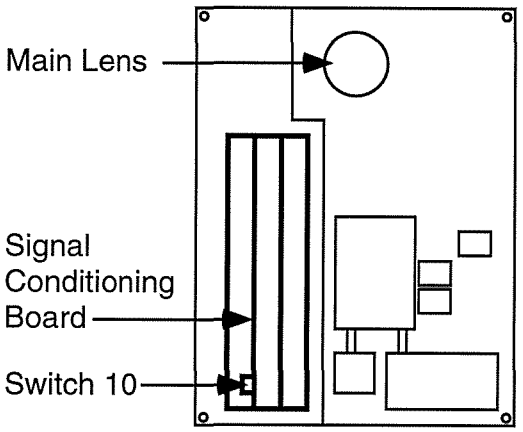


Figure A.1. Location of the Autoref vertex distance switch. The Autoref is shown in plan view with the top cover removed.

accommodation, although they may provide a proximal stimulus. The second Autoref in this study was modified so that these light sources could be turned off when required, such as when making measurements of the dark focus of accommodation.

A.2. Calibration of Autoref Readings with Subjective Refraction

Introduction

The aim of this series of experiments was to obtain calibration equations relating subjective refraction to Canon Autoref refraction readings. Previous studies have shown that Autoref best sphere readings correlate well with non-cycloplegic subjective results in adults,[1] and with cyclopleged retinoscopy results in infants.[3] However these studies conflict on the nature of the relationship between Autoref readings and subjective refraction.

Methods

In these experiments I used contact lenses of various powers to change the refractive error of a number of cyclopleged eyes. For each contact lens I performed a subjective refraction and also took a number of readings with the Autoref. I then plotted best sphere subjective refraction as a function of

Autoref best sphere reading for each subject and applied a best fit line to the data.

PROCEDURE

The examiner instilled one drop of cyclopentolate 0.5% in the subject's left or right eye, and began testing after 20 minutes. Various degrees of refractive error were induced in the cyclopleged eye by the insertion of hydrophilic contact lenses. The order of insertion of contact lenses was counterbalanced between subjects.[6]

After the contact lens had settled on the subject's eye, the examiner performed a subjective refraction and recorded the vertex distance of the trial lens in place. The subject viewed the smallest resolvable line of a Bailey–Lovie distance letter chart monocularly with their tested eye through a 5 mm artificial pupil placed at the spectacle plane. All subject's dilated pupils were larger than 5 mm. The subject then moved to the Autoref, and the examiner took five readings from the tested eye while the subject viewed a distant object monocularly with their tested eye. All Autoref readings had cylindrical components smaller than 1.00 DC.

ANALYSIS

The ocular refraction for each contact lens was calculated for infinite viewing distance and referenced to the first principal plane of the Gullstrand–Emsley eye (see section E.2).[7] I then plotted best sphere subjective refraction as a function of mean Autoref best sphere. Either linear regression or principal axis regression was used to calculate best fitting lines to the data.[8] Principal axis regression is the correct statistical method in these experiments because there is no true independent variable. However linear regression and principal axis regression yield essentially equivalent results when correlations between the two variables are high, as was the case in these experiments.

SPECIFIC CALIBRATION EXPERIMENTS

Autoref Number 1, pre January 1992 Calibration

Six subjects participated in this experiment. They ranged in age between 21 and 37 years, and had visual acuities better than or equal to 6/6. One subject was astigmatic by 0.25 DC, and the others had spherical refractions. Best sphere refractions ranged between -1.75 DS and +0.87 DS. I used linear regression to determine best fit lines for the data of each subject. I then averaged the six slope values and intercept values to obtain a mean calibration equation.

In January 1992 other researchers in the School made some alterations to Autoref number 1, making another calibration necessary.

Autoref Number 1, Post January 1992 Calibration

Two subjects from the pre January 1992 calibration participated in this experiment. Linear regression was again used to relate subjective refraction and Autoref refraction. For each subject I calculated the difference between the post January 1992 slope value and pre January 1992 slope value. The same was done for the pre and post January 1992 intercept values. I then calculated the mean shift in slope and mean shift in intercept and used these parameters to alter the pre January 1992 mean calibration equation to obtain a post January 1992 calibration equation.

Autoref Number 2, Pre October 1993 Calibration

Three subjects participated in the experiment. They ranged in age between 23 and 39 years, and had visual acuities better than or equal to 6/6. All subjects had spherical refractions and these ranged between -2.12 DS and +1.00 DS. I used principal axis regression to determine best fit lines for the data of each subject. I then averaged the slope values and intercept values to obtain a mean calibration equation.

In October 1993 Autoref number 2 was adjusted to provide refraction readings referenced to the corneal vertex, necessitating another calibration.

Autoref Number 2, Post October 1993 Calibration

The three subjects from the pre October 1993 experiment participated in this experiment. The procedures were identical to the pre October 1993 calibration.

Results

Individual calibration equation slope values were close to +1, and intercepts were close to zero (Table A.1). This indicates that the two Autorefs used in these experiments yield valid measures of best sphere subjective refraction. The mean calibration equations used at various times to relate Autoref readings and subjective refraction are summarised in Table A.2.

The calibration equation for Autoref number 1 changed after a service was made to the instrument. The calibration for Autoref number 2 also changed when the reference point was changed from a 12 mm vertex distance to a 0 mm vertex distance. These results show that researchers should perform individual calibrations for their own instruments, rather than using published calibration values.

A.3. Effect of Offgaze on Autoref Readings

The aim of this experiment was to determine if eccentric viewing affects Autoref readings. Subjective refraction does not vary much within the central 10° field,[9] so any differences observed in Autoref readings with eccentricity would be caused by Autoref error.

Methods

One 38 year old subject who was familiar with the apparatus participated in the experiment. The subject's right eye refractive error was -2.00 DS. Autoref unit number 1 was used. It was set to provide refraction readings relative to a 12 mm vertex distance. A Badal target system was mounted on top of the Autoref to present a target to the subject's right eye (see section 3.2). The Badal target had small circular fixation points at eccentricities of 2.3° and 3.7°

Table A.1. Individual calibration parameters relating Autoref readings and subjective refraction

Autoref	*Subject*	*Calibration 1*		*Calibration 2*		*Change in Parameter*	
		slope	*intercept*	*slope*	*intercept*	*Δ slope*	*Δ int.*
N° 1		*pre Jan. 1992*		*post Jan. 1992*			
	M.L.	1.01	0.15	0.97	0.64	-0.04	0.49
	D.A.A.	0.96	0.02	0.97	0.45	0.01	0.43
	C.B.–D.	1.09	-0.17				
	J.C.	0.97	-0.22				
	A.G.	0.91	-0.65				
	T.D.	0.99	-0.32				
	mean	0.99	-0.20			-0.01	0.46
N° 2		*pre Oct. 1993*		*post Oct. 1993*			
	D.A.A.	0.90	0.12	0.97	0.05		
	R.M.	0.90	-0.22	1.01	-0.07		
	L.R.S.	0.88	0.45	0.92	0.04		
	mean	0.89	0.11	0.97	0.01		

The table gives slopes and intercepts of the equation relating best sphere subjective refraction (*subj*) to Autoref best sphere refraction (*Autoref*). The equation takes the form: *subj* = slope.*Autoref* + intercept.

in left, right, up, and down directions of gaze, as well as a central fixation point.

I instilled one drop of cyclopentolate 0.5% in the subject's right eye and began testing when the amplitude of accommodation had sufficiently reduced. The left eye was occluded throughout the experiment. I instructed the subject to view one of the fixation points, and then aligned the Autoref with the centre of the subject's pupil. It is important to note that this alignment procedure reflects normal practice when using the Autoref. That is, before taking a reading the examiner always aligns the Autoref with the centre of the subject's entrance pupil, even though the subject might be fixating eccentrically (Figure A.2). A different situation occurs when the examiner initially aligns the subject's centrally fixating eye, but does not continue to keep the subject's eye aligned with time. This situation does not

Table A.2. Summary of mean calibration equations relating Autoref readings and subjective refraction

Autoref	*Date*	*Calibration Equation / Comment*	*Vertex Setting*
N° 1	< circa January 1992	*subj* = +0.988.*Autoref* - 0.2	12 mm
	circa January 1992	Service to Autoref	
	> circa January 1992	*subj* = +0.974.*Autoref* + 0.262	12 mm
N° 2	3 Jun. '93 – 18 Oct. '93	*subj* = +0.8912.*Autoref* + 0.115	12 mm
	19 October 1993	Vertex setting changed	
	≥ 19 October 1993	*subj* = +0.965.*Autoref* + 0.01	0 mm

The calibration equation gives the best sphere subjective refraction (*subj*) as a linear function of the Autoref best sphere refraction (*Autoref*). Each calibration equation is the mean of the calibration equations of a number of subjects (see text for details). 'Vertex Setting' is the vertex distance to which the Autoref referenced its readings.

occur in practice except when the examiner makes an error in aligning the eye when the eye moves.

The order of viewing of the various fixation points was counterbalanced.[6] I took Autoref readings one at a time (in counterbalanced order[6]) until I had 10 readings for each eccentric fixation point, and 20 readings for the central fixation point.

I calculated the best sphere values for each Autoref reading. All Autoref readings had cylindrical components of 0.75 DC or less. I then used stepwise multiple regression to see if Autoref readings change with eccentric viewing. I used stepwise regression because I was unsure if a polynomial term was needed in addition to a linear term in the regression equation.

Results

There is a significant effect of offgaze on Autoref readings ($R^2 = 0.39, p < 0.0001$), and the best fit equation for the subject of this study is given by

$$A_{mse} = -0.021.e_v + 0.003.e_v^2 - 0.012e_h - 2.63\ , \qquad \text{(A.1)}$$

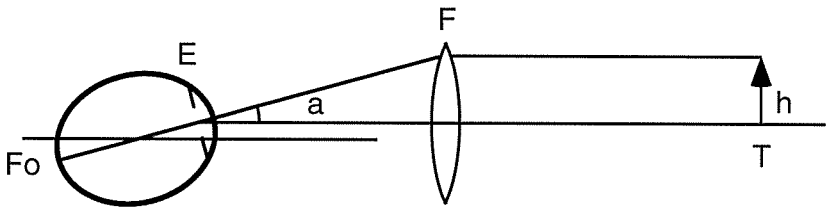


Figure A.2. Autoref alignment method for Badal target viewing. The examiner centres the Autoref and Badal system on the entrance pupil of the eye. Note that the axis of the Badal system is coincident with the axis of the Autoref (not shown). Key: fovea (Fo); entrance pupil of eye (E); angle of fixation (a); Badal Lens (F); target (T); target height (h).

where A_{mse} is the mean spherical equivalent Autoref reading, e_v is the vertical direction of gaze (degrees), and e_h is the horizontal direction of gaze (degrees). Up gaze and right gaze are considered positive in sign.

The best fit equation predicts that the Autoref readings will become 0.11 D more myopic when changing gaze along the vertical meridian from 2.5° down gaze to 2.5° up gaze. Also, the Autoref readings will become 0.06 D more myopic when changing gaze along the horizontal meridian from 2.5° left gaze to 2.5° right gaze. These changes are very small, and so changes of gaze across a 5° wide target (as in Chapter 3) would have had negligible effects on Autoref readings.

The findings of this experiment assume that the Autoref is correctly aligned with the subject's pupil. If the examiner does not realign the subject's eye after a shift in gaze then the pupil edge could cut the infra-red beam of the Autoref and lead to errors in the readings. Assuming that the subject's eye is always kept aligned, pupil size per se would only have an effect if it was smaller than 3 mm.[4]

References

1. McBrien, N.A. and M. Millodot. Clinical evaluation of the Canon Autoref R-1. *Am. J. Optom. Physiol. Opt.* 1985, **62**(11), 786–792.

2. Matsumura, S., S. Maruyama, R. Ishikawa, R. Hirano, K. Kobayashi and Y. Kohayakawa. The design of an open view autorefractometer. *In:* G.M. Breinin and I.M. Siegel eds. *Advances in Diagnostic Visual Optics.* Berlin: Springer, 1983. pp. 36–42. (Springer Series in Optical Sciences, vol. 41).
3. Aslin, R.N., S.L. Shea and H.S. Metz. Use of the Canon R-1 Autorefractor to measure refractive errors and accommodative responses in infants. *Clin. Vision Sci.* 1990, **5**(1), 61–70.
4. Winn, B., J.R. Pugh, B. Gilmartin and H. Owens. The effect of pupil size on static and dynamic measurements of accommodation using an infra-red optometer. *Ophthalmic Physiol. Opt.* 1989, **9**, 277–283.
5. Davis, B., M. Collins and D. Atchison. Calibration of the Canon Autoref R-1 for continuous measurement of accommodation. *Ophthalmic Physiol. Opt.* 1993, **13**, 191–198.
6. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin.* 1972, **77**(1), 54–64.
7. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 252–253.
8. Sokal, R.R. and F.J. Rohlf. *Biometry.* 2nd ed. San Francisco: W. H. Freeman, 1981. pp. 594–601.
9. Millodot, M. Effect of ametropia on peripheral refraction. *Am. J. Optom. Physiol. Opt.* 1981, **58**(9), 691–695.

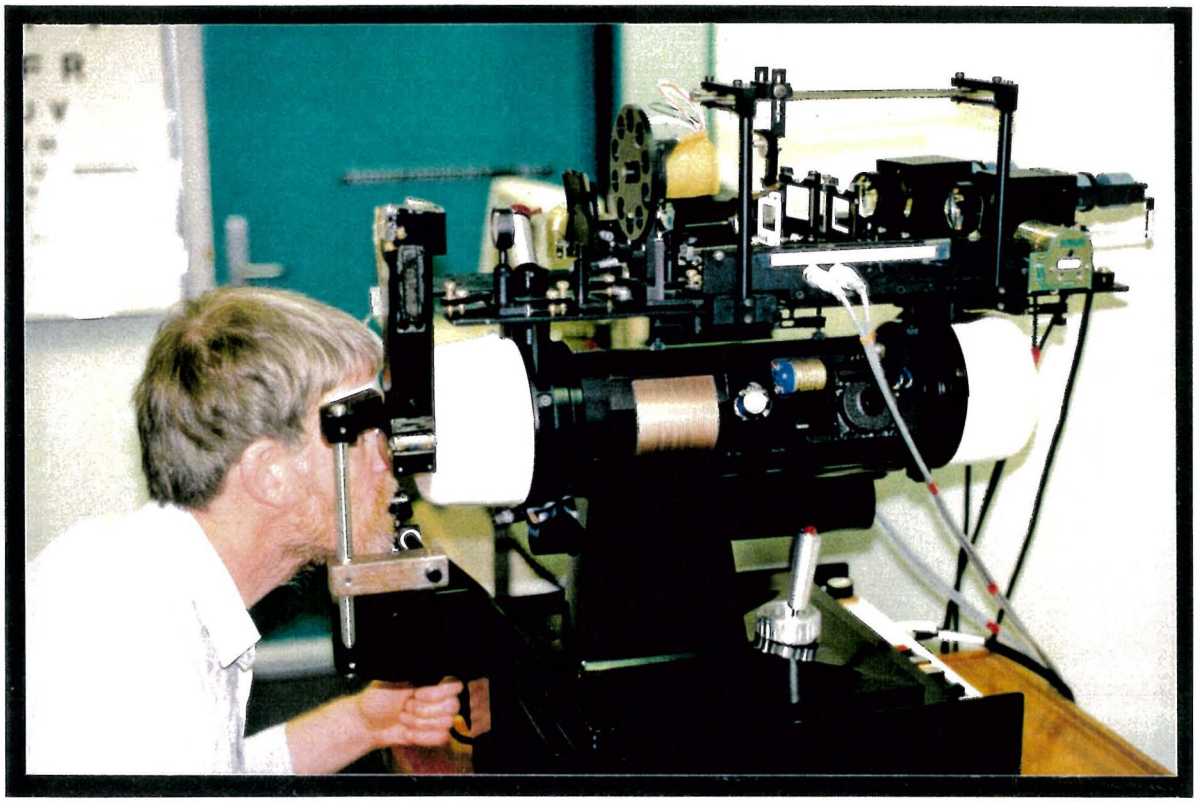
Appendix B

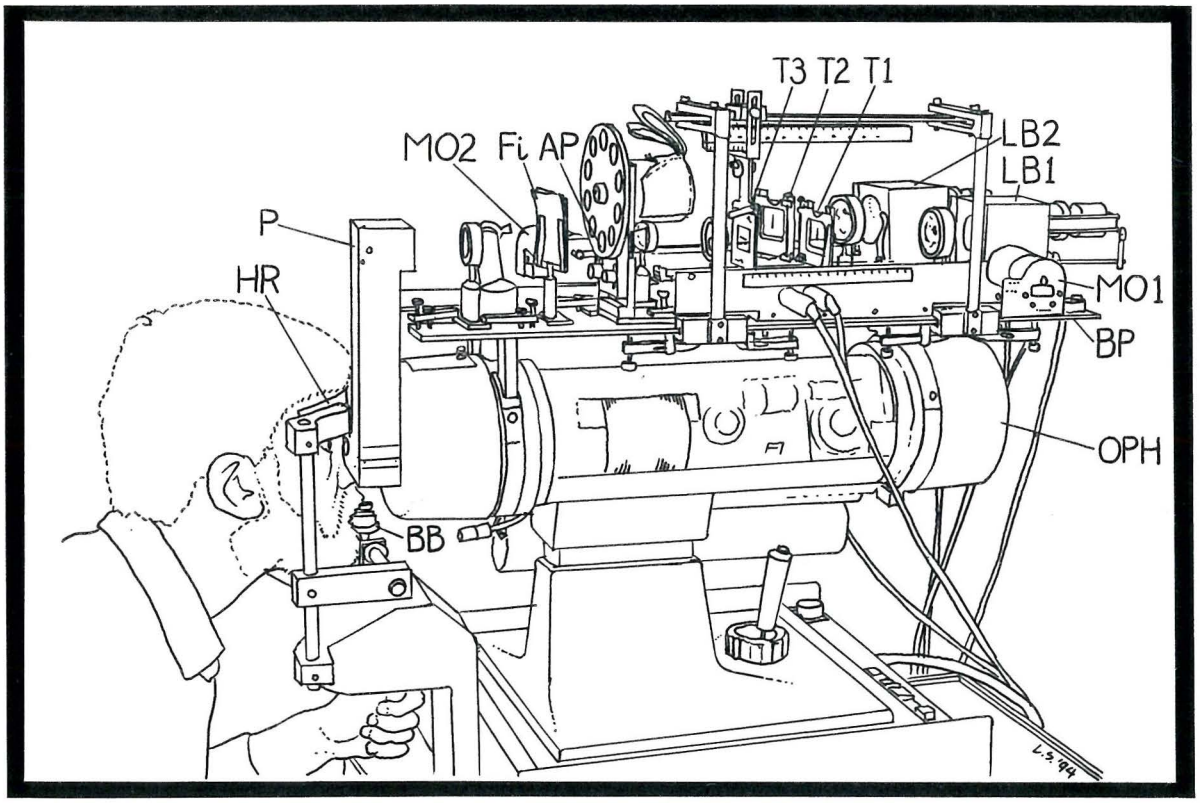
Ophthalmetron Optometer, Electronic Control Apparatus and Badal Stimulus System

B.1. Introduction

I used an Ophthalmetron optometer and associated Badal stimulus system in several of the studies reported in this thesis. A photograph of the apparatus appears in Figure B.1. The electronics of the system are shown schematically in Figure B.2, and the optics of the Badal system are shown schematically in Figure B.3.

Figure B.1. The Ophthalmetron and Badal stimulus system.
Key: Ophthalmetron optometer (OPH); base plate of Badal stimulus system (BP); head rest (HR); bite bar (BB); Badal system 'periscope' (P); light boxes (LB1, LB2); motors to drive target position (MO1, MO2); targets (T1, T2, T3); artificial pupil plane of Badal system (AP); filters (Fi).

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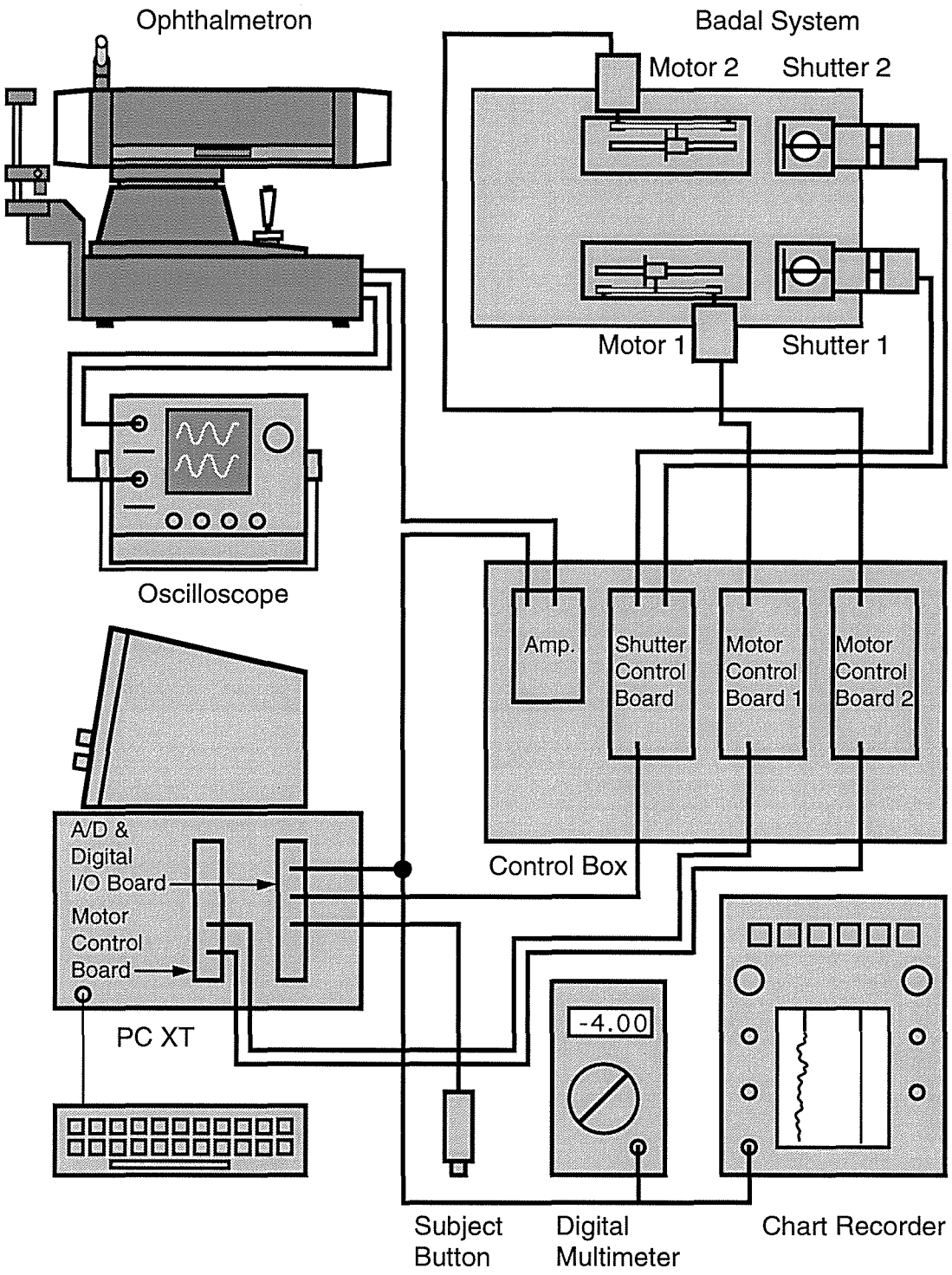

Figure B.2. Schematic diagram of the electronics of the modified Ophthalmetron optometer, the Badal stimulus system, and associated apparatus. The Badal stimulus system is shown in plan view and detached from the Ophthalmetron for clarity. The optical components of the Badal system have been omitted for clarity. See the text for a descriptions of the various components.

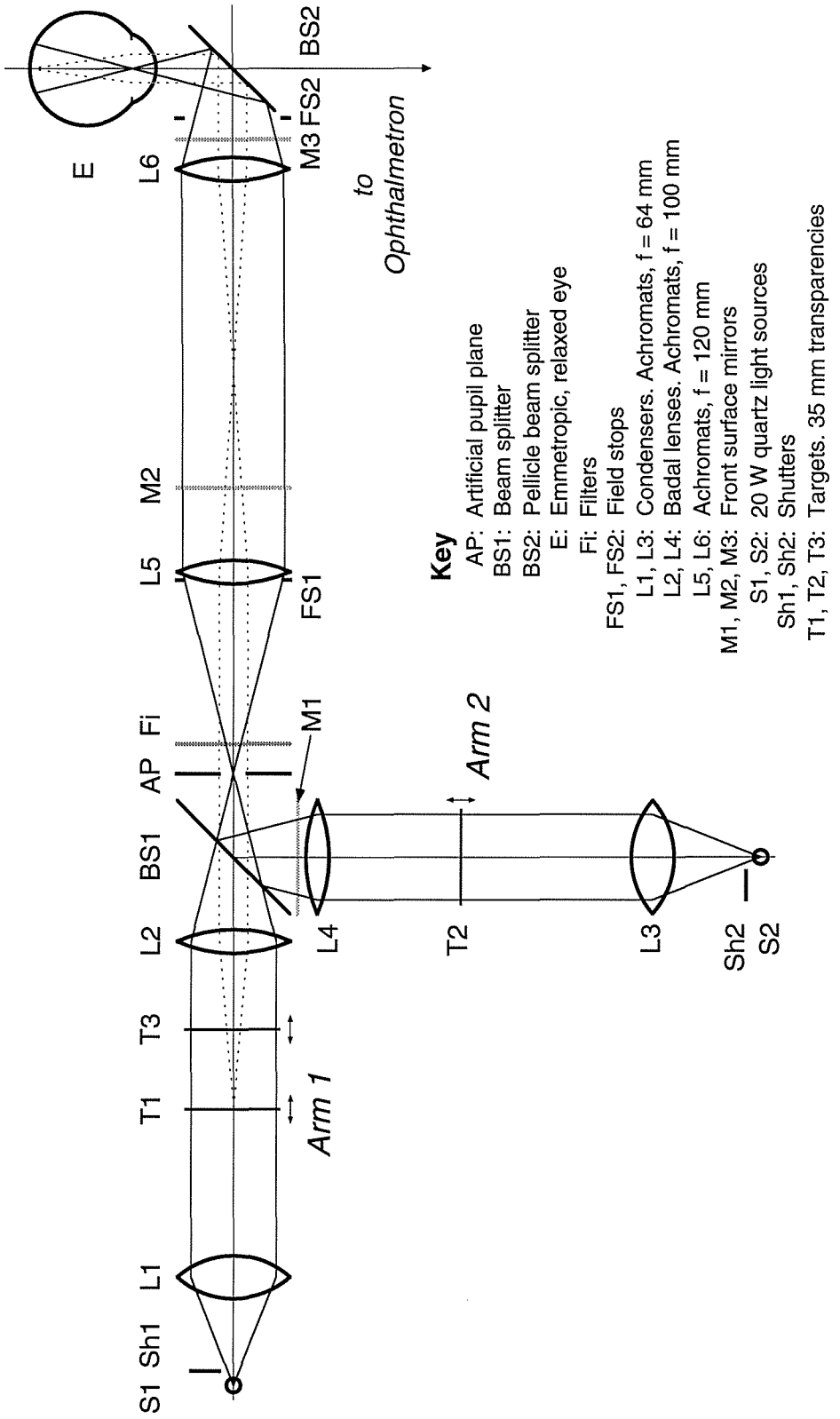

Figure B.3. Schematic diagram of the Badal stimulus system. See the text for a description of the system.

The modified Ophthalmetron optometer gives a continuous voltage output that is related to the amount of accommodation being exerted by a subject. The voltage output of the Ophthalmetron is amplified, sampled by a computer, and stored on floppy disc for later use. A Badal stimulus system is fixed on top of the Ophthalmetron. The optical system presents targets for the subject to view in one of two arms. Two targets, one in Arm 1 and the other in Arm 2, can be set to precise locations by two motors that are controlled by an interfaced computer. Both targets can be set to provide steady stimuli to accommodation. In addition, target 1 can be moved to provide an accommodation stimulus that varies in time either as a ramp or a sinusoid. A third target holder can be interposed in Arm 1 to provide two overlapping targets. This third target is set manually. The computer also controls two shutters to change the subject's view from one target arm to the other.

B.2. Ophthalmetron Optometer

Description of the Ophthalmetron

The Bausch and Lomb Safir Ophthalmetron is an objective infra-red optometer that operates on the principle of streak retinoscopy.[1,2] Knoll and Mohrman have described the design of the Ophthalmetron.[1] Ophthalmetron readings correlate well with both retinoscopy findings and subjective refraction.[3,4]

Modifications Made to the Ophthalmetron

Several modifications were made to the Ophthalmetron, and Johnson *et al.*[5] have previously performed some of these modifications on their Ophthalmetron.

MODIFICATIONS TO ALLOW CONTINUOUS MONITORING OF REFRACTIVE STATE

Meridian Motor. The meridian motor was disabled by the removal of relay K703,[6(fig.7-5)] so readings of refractive state could be taken along only one meridian of the eye. (In unmodified operation the meridian motor rotates the carriage of the Ophthalmetron to read refractive error in the various meridians of the eye.) During operation I always set the carriage of the Ophthalmetron to sample refractive error along the vertical meridian (i.e. along 90°). This setting has to be made before every trial because the periscope used to initially align the subject's eye only operates when the carriage is in its 'stand-by' position.

Trolley Servo Motor. The trolley and pen recorder were disabled by removing the connection between capacitor C603 and resistor R623 on the Servo Amplifier Assembly.[6(fig.11–4)] (In unmodified operation a servo motor drives the trolley to plot the patient's refractive error as a function of eye meridian.) The trolley was then moved so that the pen pointed to the '-1 D' position on the trolley scale. This position has not been altered since.

Output Signal from Servo Amplifier Assembly. The most important modification was one to obtain an output signal representative of the subject's refractive error. The error signal to the trolley servo motor was used for this purpose.[5] An 8.2 kΩ resistor and 10 kΩ potentiometer were inserted after the output of operational amplifier U601 on the Servo Amplifier Assembly.[6(fig.11-4)] A BNC jack was attached to the front panel and connected to the output of the potentiometer. The amplification and sampling of this signal is described in later sections.

MISCELLANEOUS MODIFICATIONS AND ADJUSTMENTS

Calibration Control Knob. The calibration control knob was initially adjusted so that a voltage signal of +1.03 V was obtained from the Control Box amplifier (see later) when the Ophthalmetron was reading from a model eye provided with the Ophthalmetron. Chocks were placed tightly under the

calibration control knob so that it could not be depressed and rotated by accident. The control knob has not been adjusted since this time.

Photodetector Signals. The two channel outputs of the Pre-amplifier Filter Assembly[6(fig.11-2)] (Channel 'A' and Channel 'B') were applied to the X and Y inputs of an oscilloscope. Channels 'A' and 'B' are amplified versions of the voltages across two photodetectors. The light falling on the photodetectors from the subject's eye is pulsed at 720 Hz, and so the voltages across the photodetectors also varies at 720 Hz. The phase difference between the signals from the two photodetectors represents the degree of refractive error. These signals were fed to an oscilloscope so that the examiner could monitor the quality of the photodetector signals when recording from a subject's eye. The photodetector signals change in magnitude or phase, or change from their usual sinusoidal shape whenever there is an eye blink or if the subject's pupil intersects the optometer's infra-red beam.

Bite Bar Assembly. The chinrest of the Ophthalmetron was removed and replaced with a bite bar assembly. The bite bar keeps the subject more stable and helps to prevent errors that occur when the eye pupil intersects the infra-red beam of the Ophthalmetron.

Removal of Patient Fixation System. The Patient Fixation System of the Ophthalmetron was removed.[1]

Refractive Correction for Periscope Use. The subject's eye is aligned in the Ophthalmetron using a 2× afocal periscope.[1] The periscope cannot be adjusted for the examiner's refractive error, so during operation the examiners in this study wore their refractive corrections.

B.3. Electronic Control Apparatus

Hardware

AMPLIFIER

The voltage output signal from the Ophthalmetron is amplified by a low pass, second order filter in the Control Box (Figure B.2). The amplifier has

good gain and phase characteristics for the frequencies of fluctuations likely to occur in the accommodation response, that is frequencies up to about 5 Hz.[7] The amplifier provides 2.95 decibels amplification within ± 3% for frequencies up to 6.3 Hz (Figure B.4). The phase lag of the filter differs by less than 12° for all input frequencies up to 6.3 Hz (Figure B.4). Note that the phase lag of the filter is about 180° for low frequencies because the filter is an inverting filter, that is, it changes the sign of the voltage input signal.

A/D & DIGITAL I/O BOARD

The output of the Control Box amplifier was sampled by an analog/digital and digital I/O board installed in an IBM XT compatible computer (Figure B.2). The board sampled analog voltage values roughly in the range ±10 Volt in increments of 0.01 Volt. The sampling rate was under computer control (see B.3 - 'Software' below). A subject button connected to the A/D board (Figure B.2) allows the subject to signal when the target is clear or blurred, but I did not use the button in any of the studies reported in this thesis.

MULTIMETER & CHART RECORDER

The output of the Control Box amplifier was also connected to a digital multimeter and a chart recorder (Figure B.2). The multimeter gives instantaneous values of the amplified Ophthalmetron signal being sampled by the computer. The chart recorder gives hard copies of the accommodation response signal.

SHUTTER CONTROL

The two shutters on the Badal system can be programmed to give the subject different targets to view. Signals from the A/D board in the computer pass to a shutter control board in the Control Box, which in turn operates the shutters. Each shutter consists of two rotary solenoids, one solenoid to open the shutter and the other to close the shutter. The shutters respond very quickly to their input signals taking only 17.5 ms to open and 20 ms to close.

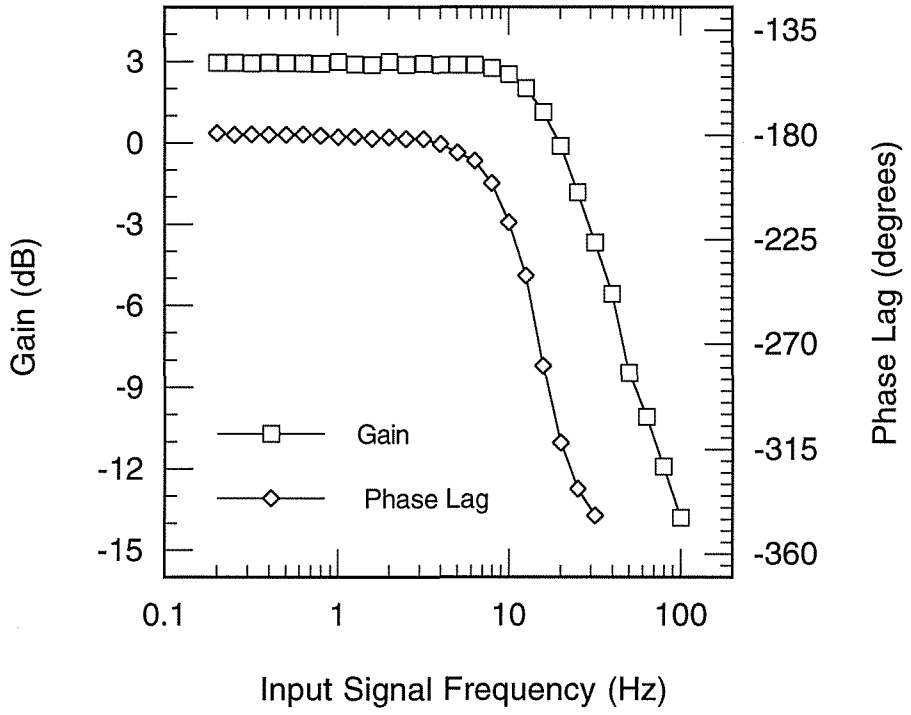

Figure B.4. Gain and phase characteristics of the control box amplifier.

The 17.5 ms opening time of the shutter is made up of 16 ms dead time and 1.5 ms transition time. The 20 ms closing time is made up of 18 ms dead time and 2 ms transition time.

MOTOR CONTROL BOARDS AND TARGET MOTORS

The computer controls the positioning of two Badal system targets. The examiner selects target position and type of motion with control software (see B.3 - 'Software' below). A motor control board installed on the personal computer receives input from the control software. Two precision motor controllers on the computer motor control board send signals to a further two motor control boards in the Control Box, which in turn drive two DC motors mounted on the Badal system. The motors move the targets back and forth on slides with belt and pulley arrangements.

Software

The user controls data acquisition, and shutter and motor position with a control program running on a personal computer (Figure B.2). On start-up the control program finds the home positions of the Arm 1 and Arm 2 targets. The program slowly moves each target along its track until the target strikes a mechanical stop at the end of the track. The home position is used as a reference for all target positioning. The program presents options to the user in various windows on the computer screen. In the IDLE state the user can change target positions and open and close shutters immediately. In the IDLE state the user also sets various parameters in anticipation of an experimental run. These parameters are described below.

DATA ACQUISITION

The user can set the rate at which the computer samples the output signal from the Ophthalmetron (1–111 Hz), and also the total number of datum points sampled.

DATA STORAGE

Data is saved on 1.44 megabyte 3 1/2 inch floppy discs.

EXPERIMENT TYPES

The data acquisition and data storage parameters described above are common to all the experimental types described below.

Amplitude of Accommodation. The subject is presented with a ramp target motion in target Arm 1. The subject can signal target blur or clarity with a subject button. The user sets the starting (and therefore ending) position of the ramp and also the extremum position of target motion. The user sets the speed of target motion (in $D.s^{-1}$). The user sets the number of cycles before data acquisition begins, and also the number of cycles after data acquisition starts.

Sine Wave. The subject is presented with a sinusoidal target motion in target Arm 1. The user sets the rest position about which the target oscillates, the

amplitude of the sine wave, and its temporal frequency (0.001–1.5 Hz). The user sets the number of cycles before data acquisition begins, and also the number of cycles after data acquisition starts.

Random Step. The subject is presented alternately with the target(s) in Arm 1 or the target in Arm 2. This is done by simultaneously opening one target Arm shutter while closing the other shutter. The user sets the positions of targets 1 and 2 with the control program, and the position of a target 3 in Arm 1 manually (if it is required). The user sets the required minimum time (0.3–100 s) and maximum time (0.3–100 s) between shutter toggles. The shutters toggle at random intervals within these minimum and maximum times. To obtain a square wave stimulus, the minimum and maximum times are set to the same value. The user also sets the initial shutter positions depending on which target is to be viewed first. The user sets the number of cycles. There are two shutter toggles per cycle.

Steady State. The subject is presented with a steady target. The user specifies the position of the target which will be viewed, and sets the shutters to make this target visible.

During an experimental run the computer acquires data, and controls shutters and motors as specified by the user.

B.4. Badal Stimulus System

The Badal stimulus system is mounted on top of the Ophthalmetron and presents targets for the subject to view (Figures B.1, B.3). Targets can be presented in one of two arms. One target in Arm 1 and one target in Arm 2 are computer controlled, while a third target in Arm 1 is set manually. The user can open or close shutters to present the target in Arm 2 or the target(s) in Arm 1 to the subject. Target 3 in Arm 1 can be swivelled out of the optical path if it is not needed.

Optical Design of Badal Stimulus System

The components of Arms 1 and 2 are almost identical and so only Arm 1 will be described (Figure B.3). Light from a 20 W Quartz source (S1) is collimated by a an achromat (L1), and passes through targets 1 and 3 (T1, T3). An achromat of 100 mm focal length (L2) acts as the Badal lens for Arm 1. Targets 1, 2 and 3 can be set to provide vergences in the range approximately -9 D to +6 D. In a Badal system target vergence is linearly related to target distance from the Badal lens.[2,8] All targets were mounted 35 mm photographic transparencies. A beam splitter (BS1) unites the light paths from Arms 1 and 2. Note the presence of a mirror (M1) in Arm 2. All mirrors in the system (M1, M2, M3) are front surface mirrors.

The light from both sources (S1, S2) is brought to a focus at an artificial pupil plane (AP). This artificial pupil plane is imaged at the subject's eye pupil by two achromats (L5, L6) which together form an afocal telescope. The important and convenient feature of this design is that the subject's entrance pupil size (and hence depth of focus) can be altered remotely by placing pupils at the artificial pupil plane. The subject views the target as if the pupil at the artificial pupil plane is at their actual pupil. This of course assumes that the subject's dilated pupil is larger than the artificial pupil. Lenses placed at the artificial pupil plane are also imaged as if at the subject's eye. In this way it is easy to correct a subject's astigmatism without clumsy trial frames and lenses placed in front of the eye. An astigmatic lens is orientated at the artificial pupil plane so that when viewed from lens 5 (L5), the axis of the astigmatic lens is rotated anti-clockwise by 90° from its axis position (standard notation) in front of the eye. For example, to correct a right eye with astigmatic prescription -1.00 DC × 30, a -1.00 DC trial lens is placed at the artificial pupil with its axis at 120° when viewed by the examiner from the direction of lens 5 (L5).

Neutral density filters (Fi) in the light path adjust the target luminance to an appropriate level. A field stop (FS1) next to lens 5 (L5) is the limiting stop of the system. This stop has a vergence at the subject's eye of + 8.3 D, and its edge would not have provided a stimulus to accommodation because it was

many dioptres beyond the subjects' far points. The field stop has a diameter in visual space of about 10°. A second field stop close to the subject's eye (FS2) is not used. A pellicle beam splitter (BS2) forms an interface between the light paths of the Badal stimulus system and the Ophthalmetron.

Calibration of Badal Target Stimulus Levels

INTRODUCTION

I performed these experiments to determine the actual target vergences of the three targets in the Badal system. I initially obtained a calibration of target vergence (D) as a function of target position (mm) for Targets 1 and 2 in Arms 1 and 2 respectively. This calibration was used in the control software so that the user could specify target position in dioptres rather than millimetres. I re-checked the calibration of target vergence in each Arm a number of times throughout the course of my studies.

METHODS

The methods in every calibration procedure were very similar. I first adjusted a telescope for my refractive error so that I could view a distant building and telescope graticule clearly with relaxed accommodation. I then fixed this telescope about 75 cm from the pellicle beam splitter (BS2 of Figure B.3) of the Badal optical system, and aligned the telescope with the optical path of the Badal system. I attached a trial lens holder to the headrest assembly of the Ophthalmetron so that it could hold a trial lens centred on the optical path of the Badal system. The trial lens was set at the assumed position of the subject's entrance pupil, which I estimated from measurements and calculations on a glass model eye provided with the Ophthalmetron. I could then view the target in the optical system through trial lenses placed in the holder. Because the trial lens is at the same position as the eye, the trial lens power needed to obtain a clear image of the target when viewing through the telescope is simply opposite in sign to the vergence of light at the eye. Differences in focus of 0.1 D are easily discerned using this method.

I determined the target vergences by placing trial lenses of various powers in the holder and then moved the target by computer or by hand to find a position of best focus.

To analyse the data I used linear regression in earlier calibrations, and principal axis regression[9] in later calibrations. The differences between these methods would have been negligible because correlation coefficients were always very close to 1.

RESULTS

The calibration equations obtained at various times are summarised in Table B.1.

Miscellaneous Matters

ALIGNING TARGETS IN THE BADAL SYSTEM

Small setting screws are used to adjust target holders 1 and 2 vertically and horizontally so as to align the respective targets with the optical axis of the Badal system. The target slide in target holder 3 is aligned by hand. A laser is used to centre slide targets on the optical axis of the Badal system.

TARGET LUMINANCE

The power supplies to quartz light sources (S1, S2 of Figure B.3) were initially adjusted to provide roughly equal brightness when viewing targets in Arms 1 and 2. A 2.2 ND filter (Fi of Figure B.3) was in place near the artificial pupil plane of the system. Except where otherwise stated, in every study involving the Ophthalmetron the power supplies to the light sources were always set to the same level, and the 2.2 ND filter was always in place. I later estimated the luminances in the target Arms under these normal conditions.

I viewed the Badal system with my right eye and an illuminated white wall behind the Ophthalmetron with my left eye. I then placed neutral density filters in front of either eye to subjectively match luminances between the two eyes. My pupil sizes were equal in the two eyes during this

Table B.1. Calibration equations relating target vergence to target position

Date	*Comments*	*Calibration Equation*		
		Target 1	*Target 2*	*Target 3*
2 Jan. 1992	Initial calibration*	$L = -0.10p + 6.06$		
20 Jan. 1992	Initial calibration*		$L = 0.10p - 8.71$	
24 Jan. 1992	Arm moved. Recal.	$L = 1.00V - 0.03$		
4 Jun. 1992	Recalibration	$L = 1.00V + 0.05$	$L = 1.00V + 0.01$	
16 Mar. 1993	Target 3 installed			$L = 0.0992p - 10.1$
c. Nov. 1993	Recalibration	$L = 1.00V - 0.05$	$L = 1.00V - 0.05$	$L = 0.1000p - 10.2$
18 Apr. 94	Recalibration	$L = 0.99V - 0.10$	$L = 0.99V - 0.13$	$L = 0.0997p - 10.2$

* Initial calibrations were performed to provide data for the control software, and were not used on experimental data. L is the target vergence in dioptres. p is the target position in millimetres. For Target 3, p is read from a scale mounted above the target holder. V is the nominal target vergence stated by the control software.

matching task. The estimated target luminance in Arm 1 was 40 cd.m^{-2}, and in Arm 2, 41 cd.m^{-2}. This luminance level is adequate for an accurate accommodation response.[10]

LIGHT SOURCE SPECTRAL CHARACTERISTICS

The spectral composition of the two light sources of the Badal system were estimated using a Topcon Luminance Colorimeter Model BM-7 (Topcon, Tokyo). The colorimeter was set to view the light source as if from the subject's viewpoint. The light source voltage supplies were set to their normal levels, and the normal neutral density filters were in place in the light path. The dominant wavelengths of the sources (relative to C.I.E. standard source A) were calculated from the chromaticity coordinates provided by the colorimeter, and using Judd's table in Wyszecki and Stiles.[11] table 3.29 To find the chromaticity coordinates of the dominant wavelengths on the C.I.E. diagram I used Table 3.3 of Wyszecki and Stiles.[11]

The chromaticity coordinates (x, y) of the Arm 1 and Arm 2 sources in XYZ colour space of the C.I.E. 1931 observer were (0.53, 0.42) and (0.55, 0.36)

respectively. The dominant wavelengths of the Arm 1 and Arm 2 sources were 590 nm and 650 nm respectively. The excitation purities of the Arm 1 and Arm 2 sources were 0.64 and 0.35 respectively.

B.5. Calibration of Ophthalmetron Output with Subjective Refraction

Introduction

I obtained individual calibrations relating subjective refraction and Ophthalmetron output for every subject in studies that used the Ophthalmetron. This direct and individual calibration procedure automatically accounts for two factors that influence the validity of infra-red optometer readings. Firstly, there is a chromatic difference of focus between the eye's peak photopic sensitivity (555 nm) and the infra-red wavelength to which the Ophthalmetron photodetectors are most sensitive (850 nm).[1] Secondly, the infra-red light of the Ophthalmetron beam may be reflected from a different plane in the eye than the plane of the retinal photoreceptors. These factors have been discussed by Charman in relation to retinoscopy.[12]

Methods

APPARATUS AND PROCEDURE

The examiner instilled a cycloplegic drug in the subject's right eye after a routine screening procedure to exclude persons susceptible to side effects. The drug and dose depended on the subject. Tropicamide 1.0% (1 drop) was used for one subject with a relatively low amplitude of accommodation. Cyclopentolate 0.5% (1 or 2 drops) or cyclopentolate 1.0% (1 drop) was used for other subjects. Cyclopleged subjective amplitudes of accommodation measured with a 5 mm artificial pupil and Rodenstock Hand Optometer ranged between 0.50 D and 2.33 D. The examiner performed a cycloplegic subjective refraction with an artificial 5 mm pupil in place at the spectacle plane. The trial lens vertex distance, and the wall chart test distance were also recorded.

The examiner then placed a trial lens on the housing of the Badal system 'periscope' (see Figures B.1, B.5). The trial lens was centred over the aperture in front of the pellicle beam splitter (BS2 of Figure B.3), and tilted slightly around its vertical axis to prevent surface reflections disrupting the Ophthalmetron photodetectors. The subject was provided with a target to view in the Badal system, placed at or beyond their far point. The examiner then aligned the subject's eye and took a short sample of the Ophthalmetron output. The above procedure was repeated for a number of trial lenses that would simulate small amounts of 'negative accommodation', relaxed accommodation, and various amounts of positive accommodation encompassing the subject's usual (non-cycloplegic) amplitude of accommodation. Readings were also taken with no trial lenses in place, as a control that the lenses themselves were not influencing Ophthalmetron output. The examiner measured the distance between the Badal system 'periscope' housing and the subject's corneal vertex for some of the trial lenses.

ANALYSIS

I first calculated the subject's true refractive error, along the 90° meridian, corrected for infinite viewing distance, and referenced to an arbitrary entrance pupil 3.05 mm behind the corneal vertex (see equation E.2 of Appendix E). The power of the trial lens along 90° was used for F_{spec} in equation (E.2), that is,

$$F_{spec} = F_s + F_c.\sin^2(90°-a)\ , \qquad \text{(B.1)}$$

where the trial lens power is expressed in its standard clinical notation as $F_s/F_c \times a$.

The next step in the analysis was to calculate the simulated refractive error of the eye when the Ophthalmetron was used to take readings from the subject's eye through trial lenses of various powers (see Figure B.5).

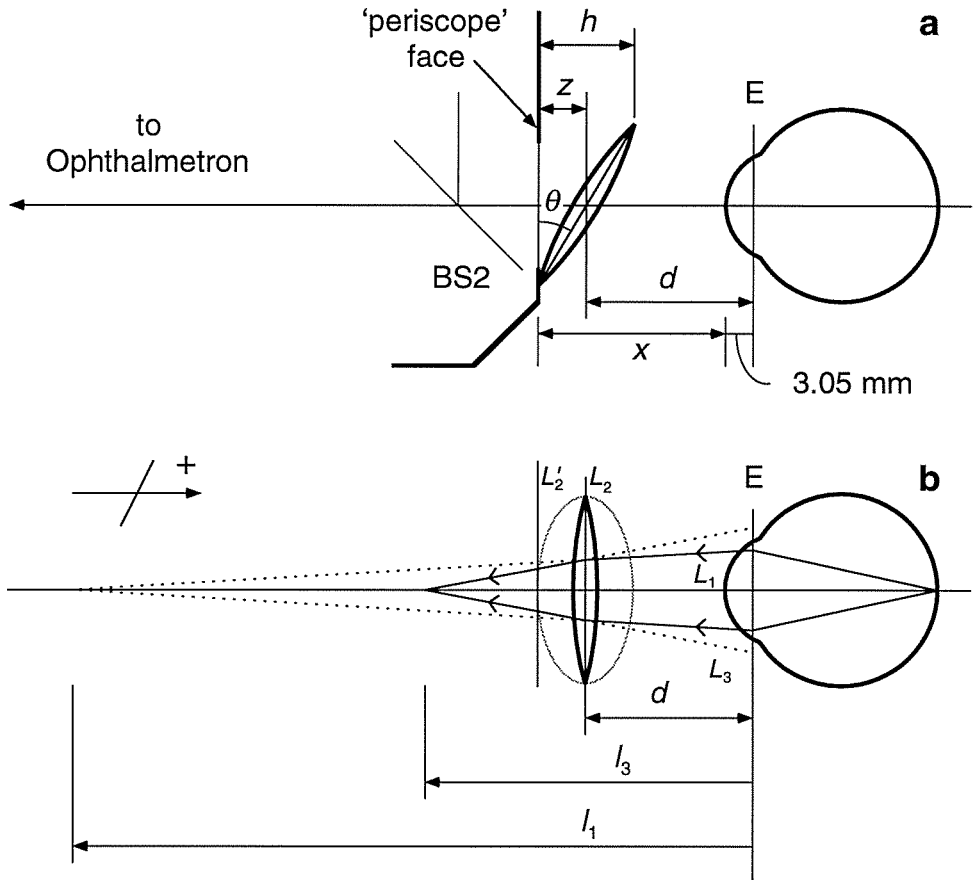

Figure B.5. Simulation of refractive errors. Part (**a**) shows the position of the subject's eye and the trial lens in relation to the Badal system in plan view. BS2 is a pellicle beam splitter also shown in Figure B.3. Part (**b**) shows the position of the subject's eye and trial lens in relation to the Badal system in side view. The shaded outline marks the edge of the trial lens. Distances l_1 and l_3 correspond to vergences L_1 and L_3 respectively. Note that the light rays travel in the reverse direction. See the text for details.

With reference to Figure B.5a, the trial lens is situated a short distance in front of the eye, and its distance from the eye is given by

$$d = x - z + 0.00305\ , \qquad \text{(B.2)}$$

where x is the measured mean distance of the subject's corneal vertex from the Badal system 'periscope' face, and where the arbitrary entrance pupil of the eye is 0.00305 m behind the corneal vertex.

The distance from the centre of the tilted trial lens to the 'periscope' face (z) is given by

$$z = \tfrac{1}{2}h\ , \tag{B.3}$$

where h is the measured height by which the trial lens is tilted away from the 'periscope' face.

Because the trial lens is tilted about a vertical axis, the effective power along its vertical axis[13] (F_l) is given by

$$F_l = F\left(1+\frac{\sin^2\theta}{2n}\right), \tag{B.4}$$

where F is the power of the spherical trial lens in place, θ is the angle of rotation of the trial lens (radians), and n is the refractive index of the trial lens material, assumed to be 1.523 (ophthalmic crown glass). The trial lens is assumed to be thin.

With reference to Figure B.5b and using a backwards ray trace, visible light from the retina of the eye is refracted along the 90° meridian, and has a vergence L_1 after leaving the entrance pupil which is simply that of the eye's refractive error along 90°, that is,

$$L_1 = K\ . \tag{B.5}$$

The vergence of the light at the trial lens is given by

$$L_2 = \frac{K}{1+dK}\ . \tag{B.6}$$

After refraction through the trial lens the light has a vergence given by

$$L_2' = L_2 - F_l\ . \tag{B.7}$$

Referring back to the entrance pupil of the eye,

$$L_3 = \frac{L_2'}{1-d.L_2'}\ . \tag{B.8}$$

L_3 is the *apparent* refractive error of the eye along 90° with the trial lens in place. Now substituting the right hand side of equation (B.7) for L_2' in equation (B.8) yields

$$L_3 = \frac{L_2 - F_l}{1 - d(L_2 - F_l)} . \qquad \text{(B.9)}$$

Substituting the right hand side of equation (B.6) for L_2 in equation (B.9) yields

$$L_3 = \frac{K - F_l - d.F_l K}{1 + d.F_l + d^2 F_l K} . \qquad \text{(B.10)}$$

Equation (B.10) gives the simulated subjective refraction of the eye. The simulated subjective refraction was calculated for each trial lens, and plotted as a function of the Ophthalmetron output for those same lenses. Polynomial regression or principal axis regression was used to find the best fit equation describing the data. I also altered the vertical axis intercept of the equation so that the line would pass through the mean data obtained with no trial lens in place. This was to account for any effects the lenses have on Ophthalmetron readings irrespective of their power. The amount of adjustment required was small, ranging from +0.09 D to -0.35 D.

Results

A sample calibration curve is shown for the data of one subject (Figure B.6). Note the highly linear relationship between subjective refraction and Ophthalmetron output over about an 8 D range. The principal axis regression line has been moved down slightly so that it will pass through the mean of the data points taken with no trial lens in place (triangle symbols). The equation in the figure is for the line after it has been adjusted.

The slopes of the individual calibration equations are all very similar, but the intercepts vary from subject to subject (Table B.2). The equation intercept for subject N.S. is quite different from the intercepts of the other subjects. The intercept for subject D.V. has a high negative value because I used the 'minus range' of the Ophthalmetron for this myopic subject.

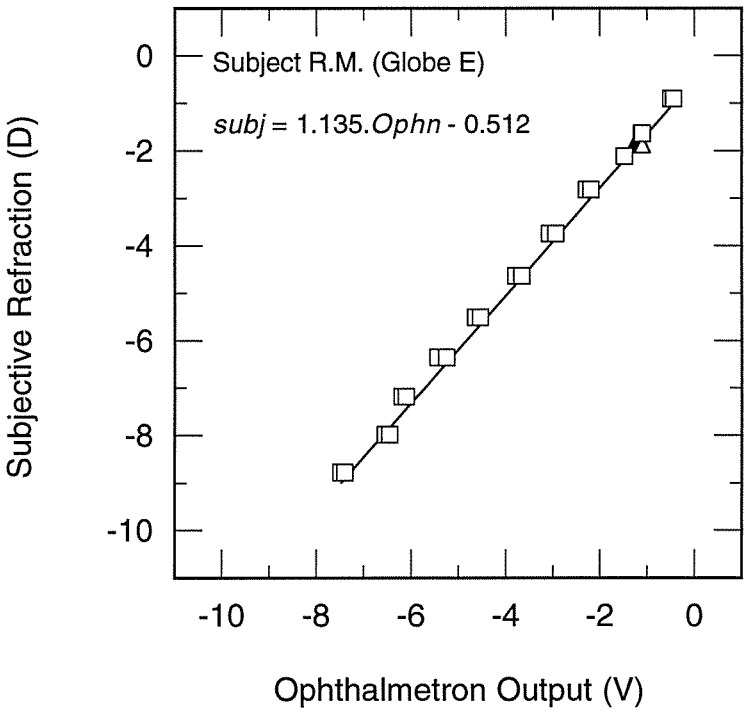

Figure B.6. Sample Ophthalmetron calibration data for subject R.M. Square symbols denote data obtained with various trial lenses in place. Triangle symbols denote data obtained without a trial lens in place. The solid line is the principal axis regression line, which has been moved down the y axis to pass through the mean of the 'no lens' data (triangles).

Discussion

The individual calibration equations listed in Table B.2 were used to obtain measures of subject accommodation in later experiments. The validity of a calibration equation depends on how accurately the examiner performed the subjective refraction. Refractions were performed under cycloplegia to within 0.25 DS and 0.25 DC, so this factor by itself would limit the accuracy of the calibration equation to about ±0.25 D. Recalibrations on two subjects (see Table B.2, subjects D.A. & R.M.) show excellent repeatability. This, coupled with the excellent short and long term repeatability of readings from a model eye (see section B.6), demonstrates that it was valid to use calibration equations over a number of experimental sessions.

Table B.2. Individual calibration equations relating Ophthalmetron output and subjective refraction

Subject	*Globe**	*Notes*	*Calibration Equation* $subj = av^2 + bv + c$			r^2	*Regression Method*
			a	*b*	*c*		
D.A.	D		-0.005	1.08	-1.24	0.999	polynomial
	E	oct 1993		1.08	-0.87	0.999	principal axis
	E	jul 1994		1.07	-0.92	0.999	principal axis
R.B.	E			1.08	-0.79	0.998	principal axis
N.C.	E			1.09	-0.84	0.997	principal axis
C.C.	D		0.002	1.12	-0.95	0.998	polynomial
A.G.	E			1.08	-0.81	0.998	principal axis
S.H.	E			1.14	-0.87	0.995	principal axis
M.J.	E			1.03	-1.48	0.998	principal axis
S.L.	E			1.10	-0.52	0.993	principal axis
M.L.	D		0.001	1.07	-0.94	0.999	polynomial
R.M.	E	oct 1993		1.15	-0.54	0.998	principal axis
	E	mar 1994		1.13	-0.51	0.998	principal axis
L.R.S.	D		-0.006	1.10	-0.78	0.999	polynomial
	E			1.11	-0.54	0.999	principal axis
M.S.	E			1.11	-0.41	0.997	principal axis
N.S.	E			1.05	0.07	0.996	principal axis
S.T.	E			1.18	-0.96	0.996	principal axis
D.V.	E	minus range†		1.06	-7.10	0.998	principal axis
R.W.	E			1.09	-1.38	0.996	principal axis
B. & L. Eye‡	E			1.10	-1.79	0.999	principal axis

* Labels were used to identify Ophthalmetron main globes used in this thesis. † The minus range of the Ophthalmetron was necessary for one myopic subject. ‡ The calibration equation for the B. & L. model eye relates simulated retinoscopic refraction to Ophthalmetron output. Individual calibration equations are of the general form, $subj = av^2 + bv + c$, where *subj* is the simulated subjective refraction (D), v is the Ophthalmetron output (V), and a, b, and c are the regression coefficients. Calibration procedures were repeated for some subjects, and dates are given in the Notes column. See the text for details.

B.6. Repeatability of Ophthalmetron Output

To assess the repeatability of Ophthalmetron voltage output, I performed repeated measures on a glass model eye (B. & L. Eye) provided with the Ophthalmetron. I assessed repeatability in the short term over 6 hours, and in the long term over several months.

Methods

SHORT TERM REPEATABILITY

I assessed short term repeatability of Ophthalmetron output by taking readings from a B. & L. eye over a period of 6 hours after instrument start up. The six hour time period was chosen as the likely maximum time for which the Ophthalmetron was powered at one session. The use of a Bausch and Lomb model eye rather than human eye is justified because the Ophthalmetron outputs from the two are similar (see Table B.2). I collected data when Ophthalmetron main globes 'C' and 'D' were installed. Globe 'C' was not used elsewhere in any studies reported in this thesis.

LONG TERM REPEATABILITY

To assess long term repeatability of Ophthalmetron readings I used data that I had collected during individual calibrations of Ophthalmetron output to subjective refraction. At the start of each session I usually took a few readings of Ophthalmetron output from the B. & L. eye. Data was available for one globe (globe 'E') over a period of several months. I did not compare across globes, because I suspect that the relationship between Ophthalmetron output and subjective refraction is dependent on the globe in place.

Results

The Ophthalmetron output increased sharply in the first half hour for Globe C, levelling out over the next few hours (Figure B.7).

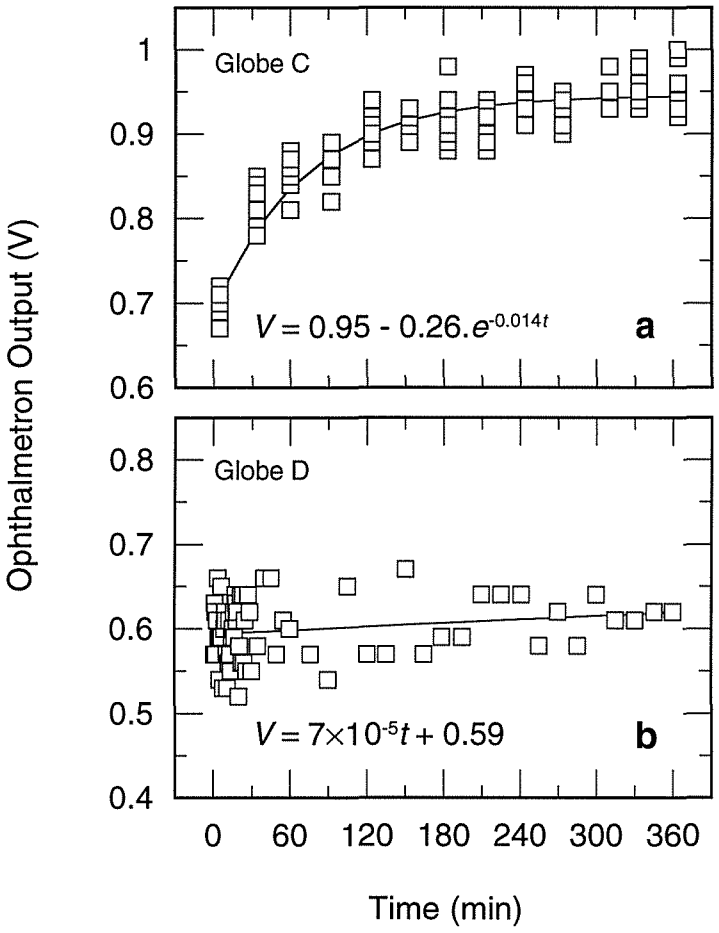

Figure B.7. Short term repeatability of Ophthalmetron output for (**a**) Main Globe C, and (**b**) Main Globe D. Best fitting exponential and linear functions are superimposed on the data for globe C and D respectively. Data were obtained from the B. & L. model eye.

With 15 – 30 minutes warm up time, Ophthalmetron output only varied by about 0.2 V over 5 1/2 hours. This corresponds to about a 0.2 D change in refraction. An exponential function performed well in describing the data ($V = 0.95 - 0.26e^{-0.014t}$, $r^2 = 0.86$), where time is measured in minutes.

For Globe 'D', Ophthalmetron output was independent of time over six hours (see Figure B.7; $V = 7\times10^{-5}t + 0.59$, $r^2 = 0.04$, $p = 0.10$), where time is measured in minutes.

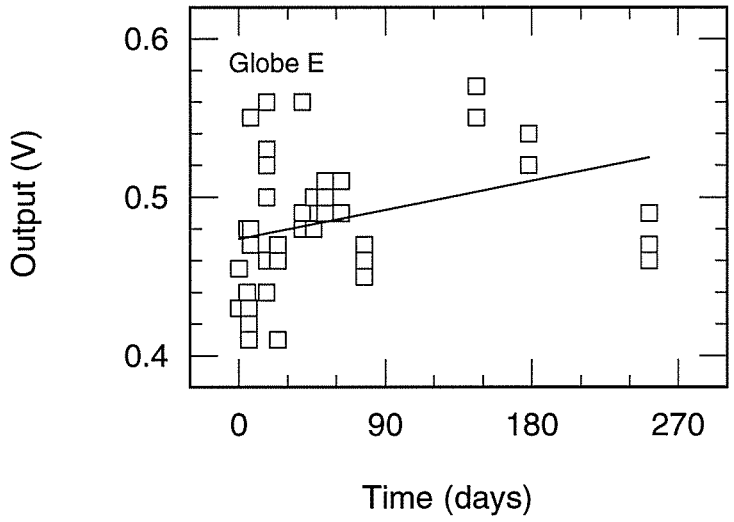

Figure B.8. Long term repeatability of Ophthalmetron output. A best fitting linear function is superimposed on the data for globe E. Data were obtained from the B & L model eye.

Ophthalmetron output for the B. & L. Eye increased significantly over a nine month period (Figure B.8), however this increase was only about 0.05 V. The linear regression equation for Ophthalmetron output (V) as a function of time in days (t) is given by

$$V = 2\times10^{-4}t + 0.47 \quad (r^2 = 0.115, p = 0.02).$$

The Ophthalmetron output shows excellent repeatability over a long time period. It should be noted that this level of repeatability was obtained without regular calibrations using the Calibration Control Knob (see also section B.2 - 'Modifications made to Ophthalmetron').

Discussion

The Ophthalmetron output for a B. & L. model eye increased slightly over a six hour period for one main globe, but not for another main globe. These differences may be due to the age of the globes. In any case, if the output of the Ophthalmetron does vary over a few hours, then it is only by a small amount.

Long term repeatability of Ophthalmetron output was excellent over a nine month period for one particular globe (globe 'E'). However it should be noted that factors such as the globe age and frequency of use may affect Ophthalmetron output. In my studies, I repeated individual calibration equations if several months had elapsed since the last calibration experimental session.

B.7. Ophthalmetron Output Noise and Frequency Characteristics

The aim of these experiments was to assess the noise level and frequency characteristics of the Ophthalmetron output signal.

Methods and Results

SPURIOUS PEAKS IN THE POWER SPECTRA
OF OPHTHALMETRON OUTPUTS

Early experiments with the Ophthalmetron revealed high frequency peaks in the power spectra of readings taken from the Bausch and Lomb model eye. These spurious peaks varied with the sample frequency, indicating the possibility of aliasing with the electrical mains frequency. To test this idea, I took samples of the Ophthalmetron signal from a B. & L. model eye in the usual way. I sampled at frequencies of 62.1 Hz, 52.9 Hz, 51 Hz, and 36 Hz, and performed 5 runs at each frequency. I then used power spectrum analysis[14] to obtain the frequency characteristics of the noise in the signals obtained from the B. & L. Eye. I used a program written by Brett Davis to perform the power spectrum analysis.

When sampling at 62.1 Hz, a peak in the power spectrum appeared at about 12 Hz, sampling at 52.9 Hz yielded a peak at 2.9 Hz, sampling at 51 Hz yielded a peak at 1 Hz, and sampling at 36 Hz yielded a peak at 14 Hz. These data clearly indicated the presence of a 50 Hz component in the Ophthalmetron output signal, probably due to the electrical mains frequency.

PROCEDURE TO CONTROL FOR SPURIOUS PEAKS IN THE POWER SPECTRA

Before starting a study I took ten samples from the B. & L. Eye at the proposed sample frequency to be used in the study. I used a calibration equation for the B. & L. Eye to convert voltage values to dioptric values (see Table B.2). I then performed power spectrum analysis to ensure there were no spurious peaks in the power spectra in the 0–6 Hz range (Figure B.9).

R.M.S. NOISE LEVELS

An examiner took 10 samples of the Ophthalmetron output from a B. & L. Eye, and either 5 or 9 samples from a two cyclopleged human eyes respectively (see section 4.3. - cyclopleged eyes control experiment).

The mean r.m.s. noise level is just 0.024 D for the B. & L. model eye. The noise level is a little higher in the two cyclopleged human eyes: 0.06 D and 0.10 D respectively.

Discussion

The r.m.s. noise levels in accommodation recordings from a model eye and a cyclopleged human eye are low. The noise levels for cyclopleged human eyes with this Ophthalmetron are similar to those reported by Johnson *et al.* for their Ophthalmetron.[5] The frequency profile of the Ophthalmetron signal is flat over the low frequency 0–6 Hz range if a suitable sample frequency is chosen. The problems with aliasing reported for the apparatus of this study demonstrates the importance of taking readings from model eyes.

B.8. Effect of Pupil Size on Ophthalmetron Output

In its normal mode of operation, the Ophthalmetron scans through the central 3 mm of the eye's entrance pupil.[15(ch. 2,p.2)] The aim of this experiment was to determine the minimum pupil size for error-free recording with the Ophthalmetron used in this thesis.

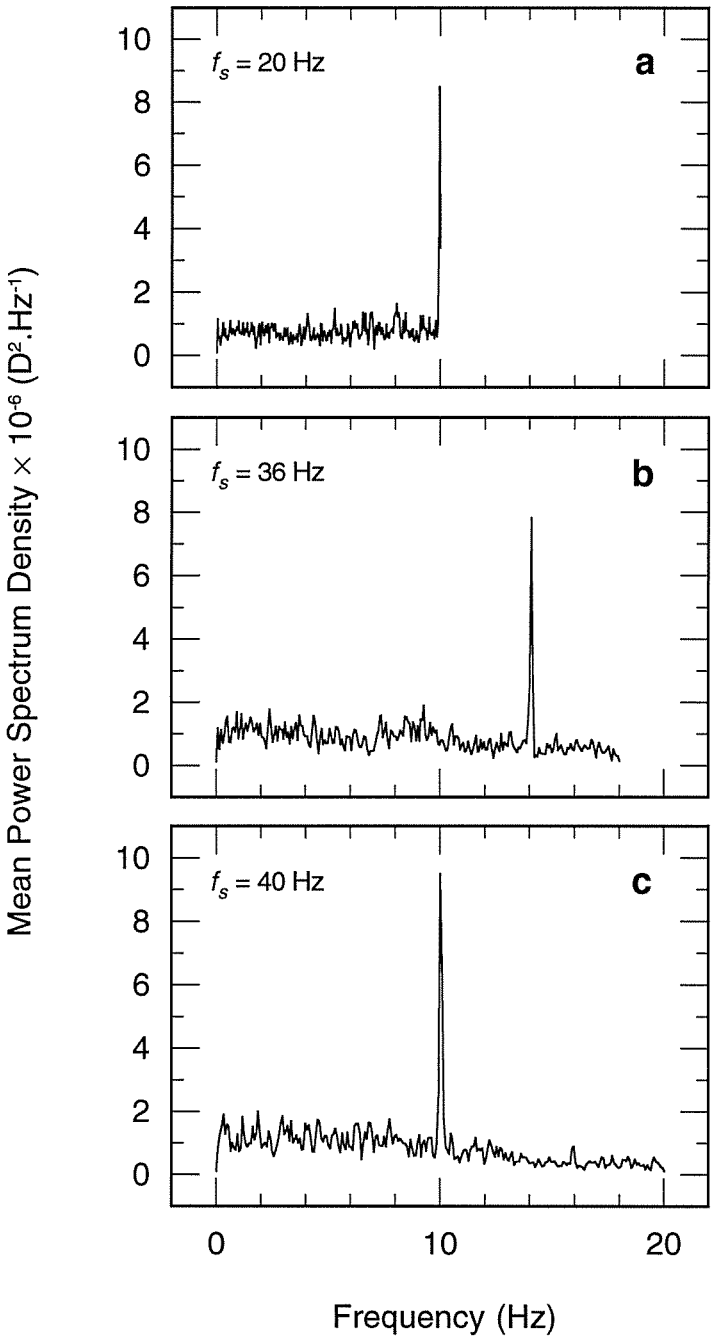

Figure B.9. Mean power spectra of Ophthalmetron signals from a B. & L. model eye at sample frequencies of (**a**) 20 Hz, (**b**) 36 Hz and (**c**) 40 Hz. Note the spurious peaks in the power spectra due to aliasing with a presumed 50 Hz component in the Ophthalmetron signal. Also note the absence of peaks in the 0–6 Hz frequency range. Each plot is the mean of 10 power spectra.

Methods

I mounted a calibrated iris diaphragm in front of a B. & L. model eye, and took 8 readings of Ophthalmetron voltage output for each combination of a number of pupil sizes (3–6 mm), and a number of trial lenses placed in front of the eye (-3 D – +8 D). The B. & L. Eye has an entrance pupil size of about 6 mm, so tested pupil sizes were smaller than or equal to this value.

Results

Ophthalmetron output was unaffected by pupils greater than or equal to 4.5 mm with all lens powers (Figure B.10). These observations were confirmed using Fisher's Protected Least Significant Difference test following an analysis of variance. For the +8 D, +4 D and -0.25 D lenses, Ophthalmetron output was not significantly different for pupil sizes of 4.5, 5, 5.5 and 6 mm ($p > 0.05$). For the -3 D lens, Ophthalmetron output was not significantly different for pupil sizes of 4, 4.5, 5, 5.5, and 6 mm ($p > 0.05$).

Discussion

In a stable eye, readings with the Ophthalmetron used in this study are not significantly affected by pupil sizes greater than or equal to 4.5 mm. However, real eyes are not stable and so it is necessary to dilate the pupil to allow a margin of error for small head and eye movements.

B.9. Effect of Offgaze on Ophthalmetron Output

In this experiment I determined whether or not Ophthalmetron output is affected when the subject changes gaze in the absence of a change in accommodation.

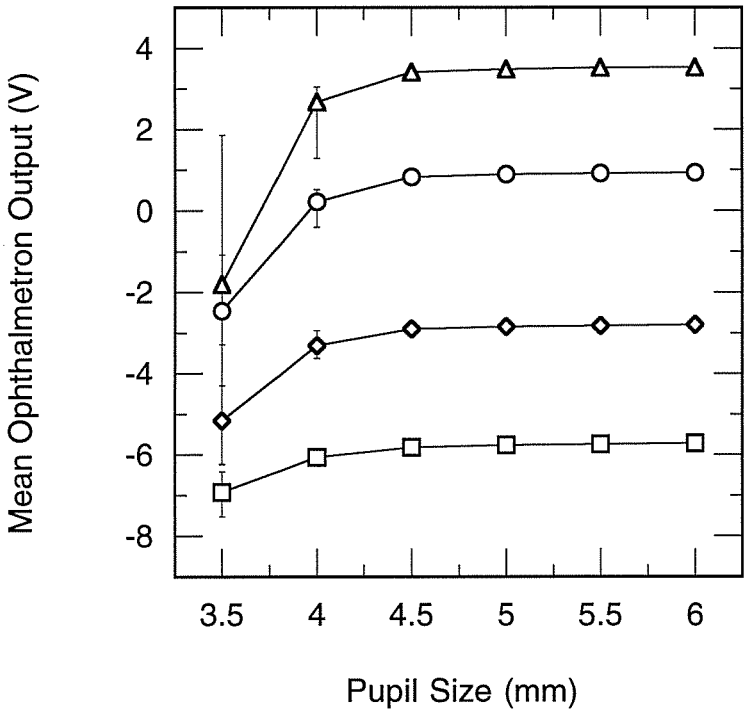

Figure B.10. Effect of pupil size on mean Ophthalmetron output voltage from a B. & L. model eye. Error bars denote the entire range of data for a particular pupil size and trial lens power. Error bars are hidden by the plot symbols in many cases. Data were obtained with lens powers of +8 D (squares), +4 D (diamonds), -0.25 D (circles) and -3 D (triangles) in front of the model eye.

Methods

I instilled 1 drop of cyclopentolate 1.0% in the right eye of a 39 year old subject to paralyse accommodation. The subject had a subjective amplitude of accommodation (using a Rodenstock hand Optometer) of 0.31 D at the start of the session, and 0.55 D at the end of the session. The subject's dilated pupil size was 7 mm at the start of the session and 6.5 mm at the end of the session.

I presented a target to the subject in the Badal system with small fixation points at eccentricities of 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3° in the up, down, left and right directions of gaze, and a central fixation point. The target was placed at the subject's far point so that it appeared clear. I first instructed the subject to view in the centre of the field of view and aligned the subject's eye.

At this stage the eye alignment light of the Ophthalmetron sometimes partially obscured the subject's view of the target. I then removed the eye alignment periscope of the Ophthalmetron, and the subject saw the fixation target clearly. Before commencing a reading, I requested the subject to view one of the various fixation points. The order of viewing of the fixation points was counterbalanced.[16] The computer sampled from the subject's eye for 5 seconds at a sample frequency of 5 Hz.

I converted the Ophthalmetron readings to refraction values using the subject's individual calibration equation, and then plotted these Ophthalmetron refraction readings as a function of gaze. I used multiple regression to fit a best fit equation to the data.

Results

Ophthalmetron refraction readings vary little with horizontal direction of gaze, but tend to become more negative in up gaze (Figure B.11). The relationship between Ophthalmetron refraction and eccentricity of gaze is described by the equation

$$Rx = -0.04e_v - 0.013e_h - 1.93 ,$$

where Rx is the Ophthalmetron refraction reading in dioptres, e_v is the vertical angle of gaze in degrees (up gaze is positive), and e_h is the horizontal angle of gaze in degrees (right gaze is positive).

Ophthalmetron refraction varies significantly in the vertical meridian (t = -5.82, $p < 0.0001$), but does not vary significantly in the horizontal meridian (t = -1.875, $p = 0.06$). It should be noted that the effect of gaze, while statistically significant, is quite small. Gaze can vary between ±1.5° in the vertical meridian, or greater than ±3° in the horizontal meridian, and Ophthalmetron refraction will only vary by 0.06 D from the refraction value for central fixation.

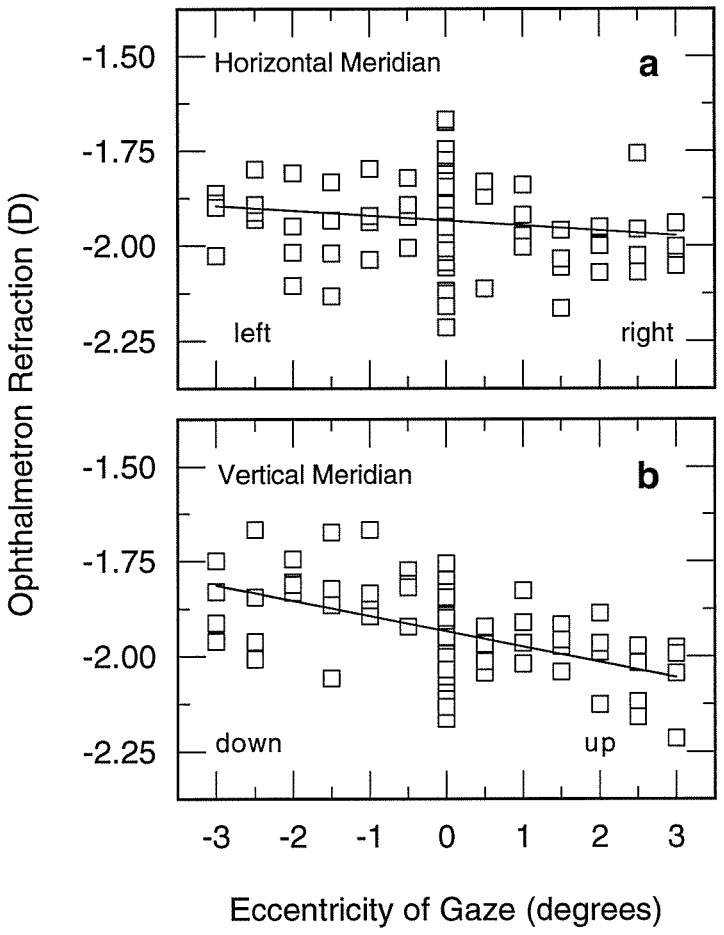

Figure B.11. Effect of eccentric fixation on Ophthalmetron refraction readings in (**a**) the horizontal meridian, and in (**b**) the vertical meridian. The line in (**a**) is the intersection of the best fitting plane with the plane of zero vertical gaze. The line in (**b**) is the intersection of the best fitting plane with the plane of zero horizontal gaze. Note that some plot symbols overlap. Data were obtained from a cyclopleged human eye.

Discussion

A subject must maintain fixation within ±1.5° in the vertical meridian so that Ophthalmetron refraction does not contain an error due to gaze greater than 0.06 D. Gaze shifts of ±3° in the horizontal meridian do not result in errors as large as 0.06 D. These limits on gaze should be within the fixation capabilities of normal subjects. Kotulak and Schor[17] reported that their

Ophthalmetron was sensitive to eye movements greater than ±0.5° from central fixation.

References

1. Knoll, H.A. and R. Mohrman. The Ophthalmetron, principles and operation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1972, **49**(2), 122–128.
2. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics.* 2nd ed. London: Butterworths, 1989. pp. 88–89; 429–430.
3. Knoll, H.A., R. Mohrman and W.L. Maier. Automatic objective refraction in an office practice. *Am. J. Optom. Arch. Am. Acad. Optom.* 1970, **47**(8), 644–649.
4. Safir, A., H. Knoll and R. Mohrman. Automatic objective refraction. Report of a clinical trial. *Trans. Am. Acad. Ophthalmol. Otolaryngol.* 1970, **74**(Nov/Dec), 1266–1275.
5. Johnson, C.A., R.B. Post and T.K. Tsuetaki. Short-term variability of the resting focus of accommodation. *Ophthalmic Physiol. Opt.* 1984, **4**(4), 319–325.
6. Bausch & Lomb. *Bausch & Lomb Safir Ophthalmetron Instruction and Service Manual.* Rochester, New York: Bausch & Lomb, 1973.
7. Charman, W.N. and G. Heron. Fluctuations in accommodation: a review. *Ophthalmic Physiol. Opt.* 1988, **8**(2), 153–164.
8. Badal, J. Optomètre métrique international du Dr Badal. Pour la mesure simultanée de la réfraction et de l'acuité visualle même chez les illettrés. *Ann. Ocul.* 1876, **75**(May/April), 101–117.
9. Sokal, R.R. and F.J. Rohlf. *Biometry.* 2nd ed. San Francisco: W. H. Freeman, 1981. pp. 594–601.
10. Johnson, C.A. Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am.* 1976, **66**(2), 138–142.
11. Wyszecki, G. and W.S. Stiles. *Color Science. Concepts and Methods, Quantitative Data and Formulas.* New York: John Wiley & Sons, 1967.
12. Charman, W.N. Some sources of discrepancy between static retinoscopy and subjective refraction. *Br. J. Physiol. Opt.* 1975, **30**, 108–118.
13. Jalie, M. *The Principles of Ophthalmic Lenses.* 4th ed. London: Association of Dispensing Opticians, 1984. p. 402.
14. Pugh, J.R., A.S. Eadie , B. Winn and G. Heron. Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic Physiol. Opt.* 1987, **7**(3), 321–324.
15. Bausch & Lomb. *Bausch & Lomb Safir Ophthalmetron Instruction Manual.* Rochester, New York: Bausch & Lomb, 1973.
16. Namboodiri, N.K. Experimental designs in which each subject is used repeatedly. *Psychological Bulletin.* 1972, **77**(1), 54–64.
17. Kotulak, J.C. and C.M. Schor. Temporal variation in accommodation during steady-state conditions. *J. Opt. Soc. Am., A, Opt. Image Sci.* 1986, **3**(2), 223–227.

Appendix C

Statistical Methods

This appendix lists a number of statistical methods used in this thesis. I have only included test which are not widely used, or which I modified.

C.1. Partial Correlations

The methods listed here are based on those cited by Pedhazur.[1] The partial correlation between variable 1 and variable 2 with the effects of variable 3 partialled out is given by

$$r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{1-r_{13}^2}\sqrt{1-r_{23}^2}}, \qquad \text{(C.1)}$$

where r_{12}, r_{13} and r_{23} are the respective Pearson correlation coefficients between variables 1, 2 and 3. This is a first order partial correlation.

Similarly, the partial correlation between variable 1 and variable 2 with the effects of variable 3 and variable 4 partialled out is given by

$$r_{12.34} = \frac{r_{12.3} - r_{14.3}r_{24.3}}{\sqrt{1-r_{14.3}^2}\sqrt{1-r_{24.3}^2}} . \qquad \text{(C.2)}$$

This is a second order partial correlation.

To test the significance of the first order partial correlation, its corresponding semipartial correlation is tested using the following statistic which has an F distribution:

$$F = \frac{R_{1.23}^2 - R_{1.3}^2}{\left(1-R_{1.23}^2\right)/\left(N-k_1-1\right)} , \qquad \text{(C.3)}$$

where $R_{1.3}^2 = r_{12}^2$, $k_1 = 2$ and $k_2 = 1$.
The test statistic has $\left(k_1 - k_2\right)$ degrees of freedom for the numerator, and $\left(N-k_1-1\right)$ degrees of freedom for the denominator. N is the number of sample points. $R_{1.23}^2$ is the multiple correlation coefficient of variable 1 regressed on variables 2 and 3 and is given by

$$R_{1.23}^2 = \frac{r_{12}^2 + r_{13}^2 - 2r_{12}r_{13}r_{23}}{1-r_{23}^2} . \qquad \text{(C.4)}$$

Similarly, the significance of the second order partial correlation can be tested using the following statistic which has an F distribution:

$$F = \frac{R_{1.234}^2 - R_{1.34}^2}{\left(1-R_{1.234}^2\right)/\left(N-k_1-1\right)} , \qquad \text{(C.5)}$$

where $k_1 = 3$ and $k_2 = 2$, and the test statistic has $\left(k_1 - k_2\right)$ degrees of freedom for the numerator, and $\left(N-k_1-1\right)$ degrees of freedom for the denominator. The multiple correlation coefficients $R_{1.234}^2$ and $R_{1.34}^2$ can be obtained using statistical packages.

C.2. The Friedman Test

The Friedman test[2] was used in Chapter 6 to test whether accommodation responses became more variable in the various conditions in this study.

The accommodation range was used as a measure of accommodation variability. The *accommodation range* is the difference between maximum and minimum accommodation responses in 20 readings from each trial. The Friedman test is normally used with variables that measure central tendency. However, it is legitimate to use the accommodation range as a variable even though it measures variability rather than central tendency. This is because the Friedman test makes no assumptions about the distribution of a variable. To control for experiment-wise error rates, two error rates were used: an uncorrected value of 0.05, and the Bonferroni corrected level. I performed two statistical contrasts at each of the two mesh distances so the Bonferroni corrected level was 0.0125 (that is, 0.05/4). In deciding the significance of a test, I used an approach recommended by Keppel.[3]

The Friedman test replaces ordinal data with their corresponding ranks, and if there are many tied values this can make the test less powerful. The original data in this study contained many ties because the Autoref optometer had a resolution of 0.12 DS and 0.12 DC. Rather than assigning mid-ranks, I took a novel approach. I broke the ties by adding a very small random number in the range $\pm 0.5 \times 10^{-5}$ to each datum point.

The Friedman test statistic has a χ^2 distribution given by

$$\chi^2 = \frac{12}{nK(nK+1)} \sum_{k=1}^{K} R_k^2 \; - \; 3n(K+1) \qquad \text{(C.6)}$$

with $\upsilon = K - 1$ degrees of freedom. In this experiment

$K = 3$ = number of conditions, and

$n = 16$ = number of subjects.

Pairwise contrasts were made on the mean ranks for the various conditions. The difference in mean rank was calculated for each condition pair (for example, $\hat{\psi} = \overline{R}_1 - \overline{R}_2$), and was considered significant if its absolute value was greater than a critical difference Δ, that is if

$$|\hat{\psi}| > \Delta \; . \qquad \text{(C.7)}$$

The critical difference in mean ranks is given by

$$\Delta = \sqrt{\chi^2_{\alpha;K-1} . \mathrm{Var}(\hat{\psi})} \; , \qquad \text{(C.8)}$$

where $\chi^2_{\alpha;K-1}$ is the percentage point of the χ^2 distribution for (K - 1) degrees of freedom and significance level α, and where

$$\mathrm{Var}(\hat{\psi}) = \frac{K(K+1)}{12}\sum_{k=1}^{K}\frac{a_k^2}{n} \,. \qquad \text{(C.9)}$$

The variables a_k are coefficients describing the contrast, and for these pairwise comparisons $a_1 = +1$ and $a_2 = -1$.

C.3. The Friedman Test for More Than One Observation per Experimental Unit

This sections describes the Friedman test for more than one observation per experimental unit, and associated post hoc comparisons,[2] as used in Chapter 7 to test for a Mandelbaum effect. Ties were removed from the data by adding a small random number to each datum value, as described in section C.2.

The Friedman test for more than one observation per experimental unit has a χ^2 distribution given by

$$\chi^2 = \frac{12}{BKn^2(nK+1)}\sum_{k=1}^{K}R_k^2 - 3B(nK+1)\,, \qquad \text{(C.10)}$$

with $\upsilon = K - 1$ degrees of freedom. In this experiment

K = 8 = number of conditions,

B = 4 = number of subjects,

n = 10 = number of accommodation readings per condition.

Post hoc contrasts involving mean ranks in the various conditions were designed to determine if there was a significant Mandelbaum effect at the various target contrast levels. The mean ranks for the 8 conditions were designated as follows:

$\overline{R}_1$ = mean response to 68% contrast C target (trial 2);

$\overline{R}_2$ = mean response to 16% contrast C target (trial 2);

$\overline{R}_3$ = mean response to 5% contrast C target (trial 2);

$\overline{R}_4$ = mean response to 0% contrast C target (trial 2);

$\overline{R}_5$ = mean response to 68% contrast C target and mesh (trial 2);

$\overline{R}_6$ = mean response to 16% contrast C target and mesh (trial 2);

$\overline{R}_7$ = mean response to 5% contrast C target and mesh (trial 2);

$\overline{R}_8$ = mean response to 0% contrast C target and mesh (trial 2);

Statistical contrasts were of the general form

$$\hat{\psi} = a_1\overline{R}_1 + a_2\overline{R}_2 + \ldots + a_k\overline{R}_k \ , \tag{C.11}$$

with the condition that

$$\sum_{k=1}^{K} a_k = 0 \ . \tag{C.12}$$

The first statistical contrast investigated whether there was a significant Mandelbaum effect present for the 68% physical contrast C target. This contrast was tested using

$$\hat{\psi} = (+1)\overline{R}_1 + (-1)\overline{R}_5 \ . \tag{C.13}$$

Similarly, statistical contrasts were performed to see whether there was a significant Mandelbaum effect for the 16%, 5% and 0% physical contrast C targets using

$$\hat{\psi} = (+1)\overline{R}_2 + (-1)\overline{R}_6 \ , \tag{C.14}$$

$$\hat{\psi} = (+1)\overline{R}_3 + (-1)\overline{R}_7 \ , \tag{C.15}$$

$$\text{and } \hat{\psi} = (+1)\overline{R}_4 + (-1)\overline{R}_8 \text{ respectively.} \tag{C.16}$$

The statistical contrast was considered significant if its absolute value was greater than a critical difference Δ, that is if

$$\left|\hat{\psi}\right| > \Delta \ , \tag{C.17}$$

where

$$\Delta = \sqrt{\chi^2_{\alpha;K-1}.\mathrm{Var}\left(\hat{\psi}\right)} \ , \tag{C.18}$$

and where $\chi^2_{\alpha;K-1}$ is the percentage point of the χ^2 distribution for $(K - 1)$ degrees of freedom and significance level of α, and where

$$\mathrm{Var}\left(\hat{\psi}\right) = \frac{Kn(nK+1)}{12}\sum_{k=1}^{K}\frac{a_k^2}{Bn} \ . \tag{C.19}$$

References

1. Pedhazur, E.J. *Multiple Regression in Behavioral Research. Explanation and Prediction.* 2nd ed. New York: Holt, Rinehart and Winston, 1982. pp. 97–134.
2. Marascuilo, L.A. and M. McSweeney. *Nonparametric and Distribution-Free Methods for the Social Sciences.* Monterey, CA: Brooks/Cole, 1977. pp. 376–378.
3. Keppel, G. *Design and Analysis. A Researcher's Handbook.* 2nd ed. Englewood Cliffs, N.J.: Prentice-Hall, 1982. pp. 162–164.

Appendix D

Control Models

Control models were implemented with the Tutsim™ block diagram simulation language (Tutsim Products, Palo Alto, CA) on an IBM PC clone.

D.1. Model of Peripheral Stimuli to Accommodation

The Tutsim model listing for the peripheral accommodation model (used in Chapter 5) is given on the next page (Figure D.1). Model parameters which were altered from subject to subject and from trial to trial are shown in bold type. Blocks 10 through 21 provide a sinusoidal stimulus to accommodation.

Blocks 114–121, blocks 214–221 and blocks 314–321 form dead space elements. In blocks 122, 222 and 322, parameter 1 is the open loop gain and parameter 2 is the controller time constant. In block 401, parameter 2 is the system dead time.

```
=Model File: c:\lawrence\per5.sim
=Date:    10 /     7 /  1994
=Time:    16 :     5
=Timing:   0.0050000  ,DELTA  ;  62.0000     ,RANGE
=PlotBlocks and Scales:
=Format:
=     BlockNo,  Plot-MINimum,  Plot-MAXimum;  Comment
=Horz:     0 ,   0.0000     ,  62.0000     ; Time
=  Y1:    23 ,   0.0000     ,   5.0000     ; AS
=  Y2:   450 ,   0.0000     ,   5.0000     ;  AR

    10 TIM
    11 CON                  P1=    0.0000      ;sine_start_time
    12 SUM     10    -11
    13 CON                  P1=    6.2831      ;2_pi
    14 CON                  P1=    0.2000000   ;sine_freq
    15 MUL     13     14     12
    16 SIN     15
    17 CON                  P1=    0.7000000   ;sine_amp
    18 MUL     16     17
    19 CON                  P1=    1.5300      ;AS_steady
    20 SUM     18     19                       ;AS_sine
    21 IFE     12     20     19                        ;
    22 PLS                  P1=    0.0500000   ;switch
                            P2=   65.0000
                            P3=    1.0000
    23 MUL     21     22                       ;AS
    24 SUM     23   -450                      ;sum_junction
   114 ABS     24
   115 SUM    114   -116
   116 CON                  P1=    0.1500000   ;DSP_1
   117 SGN    115
   118 MUL    115    119
   119 SGN     24
   120 CON                  P1=    0.0000
   121 IFE    117    118    120
   122 FIO    121          P1=    5.0000      ;Con_1
                           P2=    6.0000
                           P3=    0.0000
   214 ABS     24
   215 SUM    214   -216
   216 CON                  P1=    0.2500000   ;DSP_2
   217 SGN    215
   218 MUL    215    219
   219 SGN     24
   220 CON                  P1=    0.0000
   221 IFE    217    218    220
   222 FIO    221          P1=    5.0000      ;Con_2
                           P2=    6.0000
                           P3=    0.0000
   314 ABS     24
   315 SUM    314   -316
   316 CON                  P1=    0.5000000   ;DSP_3
   317 SGN    315
   318 MUL    315    319
   319 SGN     24
   320 CON                  P1=    0.0000
   321 IFE    317    318    320
   322 FIO    321          P1=    6.0000      ;Con_3
                           P2=    6.0000
                           P3=    0.0000
   400 SUM    122    222    322
   401 DEL    400          P1=    0.0050000   ;dead_time
                           P2=    0.3500000
                           P3=    0.0000
   403 CON                  P1=    0.5000000   ;ABIAS
   450 SUM    401    403                      ; AR
```

Figure D.1. Listing for the model of peripheral stimuli to accommodation

D.2. Models of Conflicting Stimuli to Accommodation

The models used in Chapter 8 are described below.

The Averaging Model

The Tutsim model listing for the *averaging model* is given on the next page (Figure D.2). Model parameters which were altered from subject to subject and from trial to trial are shown in bold type. Blocks 101–122 relate to the adapting and attended targets, and blocks 201–222 relate to the conflicting target.

Block 102 is the stimulus level of the adapting target, and block 101 is the difference in stimulus levels between the adapting and attended targets. Blocks 108–113 and Blocks 208–213 form fine pass filters. Blocks 114–121 and blocks 214–221 form the dead space elements. Block 201 was not used in this study. Block 202 is the stimulus level of the conflicting target.

Gain Suppression Model

The gain suppression model is a modified form of the averaging model. For the gain suppression model I simply altered parameter 1 of Block 222 to zero. This corresponds to reducing the accommodation controller gain for the conflicting target to zero. Block 222 was:

```
222 GAI    221          P1=    0.0000       ;ACG_2
```

Intermediate Resting Position Model

The intermediate resting position model is a modified form of the averaging model. To implement the intermediate resting position model I first set the various switches in the model so that the conflicting target did not appear during the viewing period, and recorded the accommodation response in the trial.

```
=Model File: b:\ls1805a.sim
=Date:     8 /     9 /  1994
=Time:    15 :    53
=Timing:   0.0050000  ,DELTA  ;  50.0000     ,RANGE
=PlotBlocks and Scales:
=Format:
=     BlockNo,  Plot-MINimum,  Plot-MAXimum;  Comment
=Horz:     0 ,   5.0000     ,  45.0000     ; Time
=  Y1:   105 ,   0.0000     ,  10.0000     ; AS_1
=  Y2:   205 ,   0.0000     ,  10.0000     ; AS_2
=  Y3:   450 ,   0.0000     ,  10.0000     ; plant_satrn

   101 PLS               P1=   25.0000      ;AS_1_inc
                         P2=   50.0000
                         P3=    0.5000000
   102 CON               P1=    3.0000      ;AS_1_adapt
   103 SUM    101   102
   104 SUM    103  -450                     ;sum_jun_1
   105 MUL    103   106                     ;AS_1
   106 PLS               P1=    1.0000      ;switch_1
                         P2=   50.0000
                         P3=    1.0000
   107 MUL    106   104
   108 ABS    107
   109 CON               P1=   10.0000      ;fine_pass_1
   110 SUM    108  -109
   111 SGN    110
   112 CON               P1=    0.0000
   113 IFE    111   112
                107
   114 ABS    113
   115 SUM    114  -116
   116 CON               P1=    0.2000000   ;DSP_1
   117 SGN    115
   118 MUL    115   119
   119 SGN    113
   120 CON               P1=    0.0000
   121 IFE    117   118
                120
   122 GAI    121        P1=    9.0000      ;ACG_1
   201 PLS               P1=   50.0000      ;AS_2_inc
                         P2=   50.0000
                         P3=    0.0000
   202 CON               P1=    6.0000      ;AS_2_conflict
   203 SUM    201   202
   204 SUM    203  -450                     ;sum_jun_2
   205 MUL    203   206                     ;AS_2
   206 PLS               P1=   25.0000      ;switch_2
                         P2=   50.0000
                         P3=    1.0000
   207 MUL    206   204
   208 ABS    207
   209 CON               P1=   10.0000      ;fine_pass_2
   210 SUM    208  -209
   211 SGN    210
   212 CON               P1=    0.0000
   213 IFE    211   212
                207
   214 ABS    213
   215 SUM    214  -216
   216 CON               P1=    0.2000000   ;DSP_2
   217 SGN    215
   218 MUL    215   219
   219 SGN    213
   220 CON               P1=    0.0000
   221 IFE    217   218
                220
   222 GAI    221        P1=    8.0000      ;ACG_2
   301 SUM    122   222                     ;sum_2_stim
   401 DEL    301        P1=    0.0050000   ;dead_time
                         P2=    0.3500000
                         P3=    0.0000
   402 FIO    401        P1=    1.0000      ;phasic_controller
                         P2=    6.0000
                         P3=    0.0000
   403 CON               P1=    0.7500000   ;ABIAS
   450 LIM    402   403  P1=    0.2500000   ;plant_satrn
                         P2=    8.0000
```

Figure D.2. Listing of the averaging model of conflicting stimuli to accommodation.

```
106 PLS                 P1=    1.0000      ;switch_1
                        P2=   50.0000
                        P3=    1.0000
 ⋮
206 PLS                 P1=   50.0000      ;switch_2
                        P2=   50.0000
                        P3=    1.0000
```

I then set the switches so that the attended target did not appear in the viewing period, and recorded the accommodation response in the trial.

```
106 PLS                 P1=    1.0000      ;switch_1
                        P2=   25.0000
                        P3=    1.0000
 ⋮
206 PLS                 P1=   25.0000      ;switch_2
                        P2=   50.0000
                        P3=    1.0000
```

I took the response in the viewing period as the one which was closest to the dark focus.

Appendix E

Miscellaneous Calculations

This appendix describes a number of calculation commonly made throughout the thesis that were required to determine the stimulus to and response of accommodation in a particular situation.

E.1. Form of Ophthalmetron Calibration Equation

The calibration equations used in this study have the form

$$K_a = a.v^2 + b.v + c, \qquad \text{(E.1)}$$

where K_a is the refractive error of the accommodating eye along 90°, for infinite viewing distance, and referred to an arbitrary entrance pupil 3.05 mm behind the corneal vertex;[1] where v is the Ophthalmetron voltage output; and where a, b and c are the individual calibration equation parameters (see section B.5).

E.2. Calculation of Ocular Refraction

Ocular refractions in this thesis were for infinite viewing distance and referred to either the entrance pupil or the first principal plane of the Gullstrand–Emsley eye.[1] The entrance pupil was used as a reference point in studies that used the Ophthalmetron optometer (Chapters 4, 5, 8), and the first principal plane was used in studies that used the Canon Autoref exclusively (Chapters 6, 7).

The subjective refraction is given in standard clinical form as $F_s / F_c \times a$, The spectacle refraction was performed with trial lenses (assumed to be thin) placed a distance d from the corneal vertex. The subject viewed a letter chart at a viewing distance of ℓ_1. It can be shown that in this situation the ocular refraction along a particular meridian of the eye is given by

$$K = \frac{\frac{1}{\ell_1} + F_{spec}}{1 - (d + r).\left(\frac{1}{\ell_1} + F_{spec}\right)}, \qquad \text{(E.2)}$$

where r is the distance from the corneal vertex to the ocular reference point used in the particular study. For studies using the Ophthalmetron, r = 0.00305 m, which is the distance from the corneal vertex to the entrance pupil of the Gullstrand–Emsley eye.[1] For studies using the Autoref, r = 0.00155 m, which is the distance from the corneal vertex to the first principal plane of the Gullstrand–Emsley eye. F_{spec} is the power of the trial lens along the meridian of interest. Equation (E.2) can be applied to both principal meridians of an astigmatic trial lens in turn to yield the ocular refraction in clinical form: $K_s / K_c \times a$.

E.3. Calculation of Accommodation Stimulus and Response

Stimulus to Accommodation

OPHTHALMETRON OPTOMETER AND BADAL SYSTEM

The stimulus to accommodation is given by

$$AS = K_s - L - F_{supp}\ . \qquad \text{(E.3)}$$

AS is the stimulus to accommodation where higher positive values correspond to targets close to the subject. K_s is the ocular sphere power of the subject's right eye. There is no need to include the ocular cylinder power because in studies that used the Badal stimulus system (Appendix B) the ocular astigmatism was corrected for all subjects with trial lenses placed at the artificial pupil plane of the system. L is the target vergence, obtained from calibration equations which relate the nominal target setting in the Badal stimulus system to the actual vergence of the target (see Appendix B.4). F_{supp} is the power of the supplementary sphere (when used) placed at the artificial pupil plane of the Badal system.

CANON AUTOREF OPTOMETER

In the studies described in Chapters 6 and 7 subjects were corrected with trial lenses placed in front of the eye. The actual stimulus to accommodation can be calculated from the target distance, the subject's ocular refraction, the trial lens power in place, and the trial lens vertex distance. If the subject is astigmatic then the stimulus to accommodation is slightly different for detail oriented along the two principal meridians of the eye. However these differences were ignored, and the mean spherical equivalent trial lens power and the mean spherical equivalent ocular refraction were used in calculations.

The mean spherical equivalent trial lens power is given by

$$F_{mse} = F_s + \frac{F_c}{2}, \tag{E.4}$$

and the mean spherical equivalent ocular refraction is given by

$$K_{mse} = K_s + \frac{K_c}{2}. \tag{E.5}$$

With reference to Figure E.1, light from the target has a vergence at the eye's first principal plane given by

$$L_2 = \frac{L_1'}{1-(d+p).L_1'}. \tag{E.6}$$

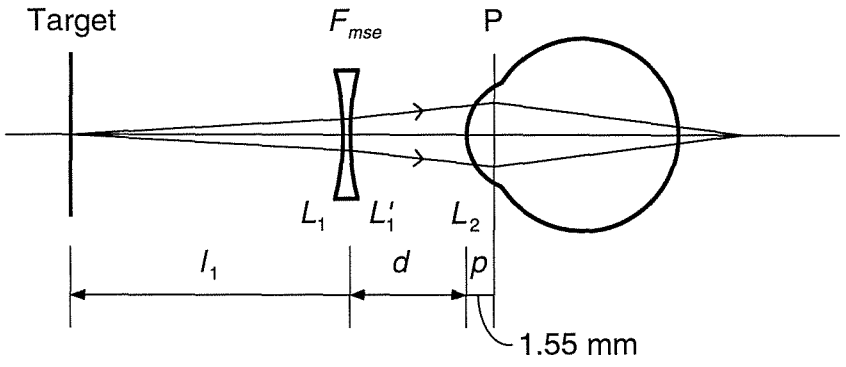

Figure E.1. Calculation of the stimulus to accommodation. See the text for details.

The stimulus to accommodation is the ocular refraction less the vergence of the incident light, and is given by

$$AS = K_{mse} - L_2 \,. \tag{E.7}$$

From equations (E.6) and (E.7)

$$AS = K_{mse} - \frac{\frac{1}{\ell_1} + F_{mse}}{1-(d+p).\left(\frac{1}{\ell_1} + F_{mse}\right)} \,. \tag{E.8}$$

Equation (E.8) was used to calculate the stimulus to accommodation.

Response of Accommodation

OPHTHALMETRON OPTOMETER

The accommodation response when data was gathered with the Ophthalmetron is given by

$$AR = K_{vert} - K_a \,. \tag{E.9}$$

K_{vert} is the ocular refraction of the subject's eye along 90°. K_a is the refractive error of the accommodating eye along 90° and is given by equation (E.1).

CONVERSION OF CANON AUTOREF OPTOMETER RESPONSES FOR COMPARISON WITH OPHTHALMETRON RESPONSES

The calibration equations for the Autoref referred refractive changes to the principal plane of the eye, so the following calculations were needed to refer

these readings to the entrance pupil of the eye for comparison with Ophthalmetron refraction readings.

In the studies where a comparison between Ophthalmetron and Autoref readings was made, the subject did not wear a correction when readings were taken with the Autoref, so the accommodation response in this case is given by

$$AR = K_{mse} - K_{amse} \,, \tag{E.10}$$

where K_{mse} is the mean spherical equivalent ocular refraction referred to the eye's entrance pupil and given by $(K_s + K_c / 2)$, and where K_s is the ocular sphere power and K_c is the ocular cylinder power. K_{amse} is the mean spherical equivalent ocular refraction of the accommodating eye referred to the eye's entrance pupil.

K_{amse} is calculated from the Autoref mean sphere readings which are referred to the eye's *principal plane*. Using a formula for effectivity

$$K_{amse} = \frac{K_{canon}}{1-(e-p)K_{canon}} \,, \tag{E.11}$$

where K_{canon} is the Autoref mean spherical equivalent refraction referred to the principal plane of the eye, e is the 0.00305 m distance from the corneal vertex to the entrance pupil of the relaxed Gullstrand–Emsley eye,[1] and p is the 0.00155 m distance from the corneal vertex to the first principal plane of the relaxed Gullstrand–Emsley eye. K_{canon} is given by

$$K_{canon} = b_a A_{mse} + c_a \,, \tag{E.12}$$

where b_a and c_a are calibration equation parameters relating Autoref readings to subjective refraction (see section A.2), and A_{mse} is the mean spherical equivalent Autoref reading given by

$$A_{mse} = A_s + \frac{A_c}{2} \,, \tag{E.13}$$

and A_s is the sphere component of the Autoref reading, and A_c is the cylinder component of the Autoref reading.

CANON AUTOREF OPTOMETER

The accommodation response was calculated from the Autoref readings, from calibration equations for the Autoref, the subject's ocular refraction, the trial lens power in place, and the trial lens vertex distance. The mean spherical equivalent trial lens power and the mean spherical equivalent ocular refraction were used in calculations (see equations E.4 and E.5).

With reference to Figure E.2, and using a reversed sign convention, visible light from the retina of the eye has a vergence after leaving the accommodating eye given by

$$L_1 = AR - K_{mse} \,, \tag{E.14}$$

where AR is the accommodation response and K_{mse} is the mean spherical equivalent ocular refraction.

The light has a vergence at the trial lens given by

$$L_2 = \frac{AR - K_{mse}}{1 - (d+p).(AR - K_{mse})} \,, \tag{E.15}$$

and a vergence after refraction by the trial lens given by

$$L_2' = \frac{AR - K_{mse}}{1 - (d+p).(AR - K_{mse})} + F_{mse} \,. \tag{E.16}$$

Referring L_2' back to the principal plane of the eye,

$$L_3 = \frac{L_2'}{1 + (d+p).L_2'} \,. \tag{E.17}$$

Now L_3 is the negative of the apparent refractive error of the eye as seen by the Autoref optometer, that is,

$$K_a = -L_3 \,. \tag{E.18}$$

Note that the apparent refractive error of the eye is obtained by applying a calibration equation to the Autoref readings (see section A.2). The apparent refractive error of the eye is given by

$$K_a = b_a A_{mse} + c_a \,, \tag{**E.19**}$$

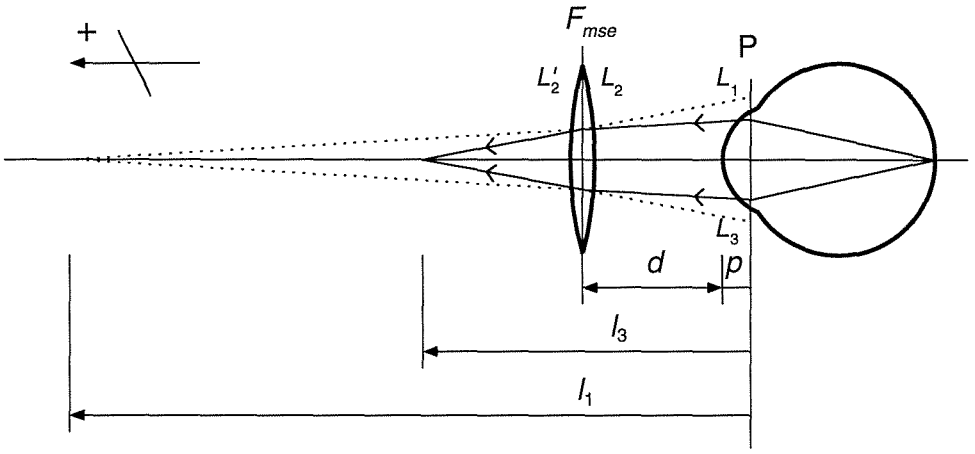

Figure E.2. Calculation of the response of accommodation. See the text for details.

where b_a and c_a are experimentally determined calibration equation parameters, and where A_{mse} is the mean spherical equivalent Autoref reading given by

$$A_{mse} = A_s + \frac{A_c}{2} . \tag{E.20}$$

A_s is the sphere component of the Autoref reading, and A_c is the cylinder component of the Autoref reading.

Rearranging equation (E.16),

$$L_2' = \frac{(AR - K_{mse}) + F_{mse}\left(1 - (d+p).(AR - K_{mse})\right)}{1 - (d+p).(AR - K_{mse})} . \tag{E.21}$$

Substituting the right hand side of equation (E.21) for L_2' in equation (E.17) gives,

$$L_3 = \frac{AR - K_{mse} + F_{mse} - (d+p)F_{mse}.AR + (d+p)F_{mse}.K_{mse}}{1 + (d+p)F_{mse} - (d+p)^2 F_{mse}.AR + (d+p)^2 F_{mse}K_{mse}} . \tag{E.22}$$

Substituting the right hand side of equation (E.22) for L_3 in equation (E.18) and rearranging for AR,

$$AR = K_{mse} - \frac{(d+p)K_a F_{mse} + K_a + F_{mse}}{1 - (d+p)^2 K_a F_{mse} + (d+p)F_{mse}} . \tag{E.23}$$

Equations (E.19) and (E.23) were used to calculate the response of accommodation.

Reference

1. Bennett, A.G. and R.B. Rabbetts. *Clinical Visual Optics*. 2nd ed. London: Butterworths, 1989. pp. 252–253.

* * *

Don't look to the left
Don't look to the right
Just follow that strait old line

Neil Finn